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HYDROTHERMAL FORMATION OF CLAY MINERALS IN THE LABORATORY

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ABSTRACT

A number of feldspars and other alumino-silicate minerals were exposed to CO_2-charged percolating water under high pressures and temperatures in a reaction chamber. A study of the end products indicated that the least stable of these materials readily broke down to form clay minerals, the greatest reaction rate occurring at 300°C. and a maximum CO_2 pressure. It was interesting to notice that the parent minerals were stable at temperatures outside of the range of 250°C. to 350°C. The production of clay minerals similar to, if not identical with, kaolinite, beidellite, sericite, pyrophyllite and gibbsite was accomplished. The resulting end product seems to be determined by the nature of the parent rock as well as by the temperature and acidity during the reaction.

INTRODUCTION

This investigation is a continuation of the preliminary work reported last year,[1] where a percolating type of reaction chamber was used to break down the three feldspars, albite, orthoclase and anorthite. In the present investigation the runs on these feldspars were repeated to determine the reaction rates over the complete range of temperature and CO_2 pressure available; and purer samples of the end product were obtained for study. In addition, a number of other minerals containing alumina and silica were studied to see if any light could be shed on the mechanism of formation of the clay minerals under hydrothermal conditions. In other words, what factors cause the formation of kaolinite, for example, rather than sericite? Are they the temperature, acidity, or parent rock? Does the clay mineral serve as the end member of a series of intermediate products, or is it formed directly? While these questions have not been definitely answered, we can begin to see a little further towards the answer than was possible before.

PREVIOUS WORK

No discussion of the previous work on the synthesis of clay minerals will be given here because this has been so completely covered by Morey and Ingerson[2] in a recent publication.

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[1] Norton, F. H. (1937). The accelerated weathering of feldspars, *Am. Mineral.*, vol. **22**, p. 1.

APPARATUS

The apparatus was the same as that used in the previous work. Three new units were constructed, making a total of five, which have been running continuously for a year and a half. A special suction pump was used to draw a definite amount of air through the condensing tubes to give, as far as possible, uniform percolation.

During a run the sample was always covered with liquid which slowly flowed down through the mass. However, the reaction started at the upper surface of the specimen and worked down, but seldom more than a few millimeters. All the samples used in the tests were taken from a slice one millimeter thick from the top of the specimen. In many cases the depth of reaction could readily be observed by a change in color and consistency.

The total pressure in the reaction chamber under the various conditions is shown in the table below.

TABLE 1

TOTAL PRESSURE IN REACTION CHAMBER IN LBS./SQ. IN.

CO_2 pressure at room temperature	250°C.	275°C.	300°C.	325°C.	350°C.
0	560	860	1230	1720	2380
125	775	1087	1467	1967	2638
250	990	1313	1703	2215	2895
375	1205	1540	1940	2460	3154
500	1420	1765	2175	2710	3410

RAW MATERIALS

Albite. This material was the same as used in the previous work.

Nephelite. This is not pure material, as it comes from a syenite rock from Ontario which has been processed to remove the iron minerals. Some albite undoubtedly remains. The approximate composition is:

TABLE 2

SiO_2	51
Al_2O_3	30
Na_2O	13
K_2O	3

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[2] Morey, G. W., and Ingerson E. (1937). The pneumatolytic and hydrothermal alteration and synthesis of silicates, *Paper No.* **937**, *Geophysical Laboratory, Carnegie Inst. of Washington.*

Orthoclase. This material was the same as that used in the previous work.

Leucite. This material came from large, perfect crystals found at Albano, Italy.

Petalite. This lithium mineral came from West Paris, Maine. Its exact composition is unknown.

Spodumene. This is concentrated material from a deposit near Fitchburg, Mass.

Lepidolite. An apparently pure mineral but its source was unknown.

Anorthite. This is the same material used in the previous investigation.

Beryl. This sample came from a clear crystal found at West Paris, Maine.

Pollucite. This cesium mineral comes from West Paris, Maine. Its purity is unknown.

Kaolinite. A washed English china clay.

RATE OF REACTION AND END PRODUCTS

The materials were ball milled and decanted in water to give a sample having particles all under 1 micron in diameter. The test procedure was the same as previously described, except that the rate of percolation was more carefully controlled.

As the crystal sizes in all cases were too small for petrographic identification, the x-ray powder method was used extensively. Patterns of the original mineral and the alteration product were taken in each case. From these it was possible to estimate the amount of conversion by the relative intensity of the lines; a rapid and simple method. However, it should be realized that the determination of the amount of alteration is not better than $\pm 10\%$ and may reach an error in some cases as great as $\pm 20\%$. Also, it is probable that a mineral mixed with another up to as much as 15% would not be detected by this method. This is sufficiently accurate for our present purpose, although for future work a chemical analysis to supplement the x-ray data would be desirable in every case.

The thermal method of analysis was also used in every case where a large enough sample was available. This method has been used extensively to identify the clay minerals, and in general is quite satisfactory.

It is necessary to use the greatest care in making an identification of the clay minerals. The crystal size is so small and the crystallization so imperfect that the x-ray diagrams do not have the sharp, distinct lines usually found. Also the background haze is much greater than with more perfectly crystalline materials. Therefore, it is sometimes easy to imagine that an end product coincides with one of the clay minerals, when actually it has real differences. In general the thermal curves show a water loss at lower temperatures for the synthetic mineral than for the natural one, indicating less perfect crystallization. This naturally decreases the usefulness of the thermal curves for identification purposes.

There is reason to believe, and this has been confirmed by other experimenters, that the synthesized minerals may differ slightly from their natural prototypes. Here the lines in the *x*-ray patterns are sometimes shifted slightly, or even suppressed. This again increases the difficulty of identification. Therefore caution is used here in expressing a definite opinion as to the crystal identity in many cases, although the class of clay mineral to which it belongs is quite certain.

It is thought most convenient to take up each original mineral in turn and discuss the reaction rate and identity of the end product. The rate is expressed as per cent converted, in a run of 320 hours as an average, in the top millimeter of sample.

The amount of conversion is plotted on a pressure-temperature diagram by means of contour lines. That is, the vertical scale expresses acidity of the solution, the horizontal scale the temperature, and each contour represents a zone of equal reaction rate.

ALBITE

This feldspar is a comparatively stable material and shows little conversion under any of the test conditions as shown in Table 3 and Fig. 1. In fact, the conversion is so slow that it was impossible to determine the nature of the end product in these tests until recently. Now it is fairly certain that the new product is beidellite because only a few new lines appear in the *x*-ray pattern and these correspond to this mineral, as shown in the appendix.

TABLE 3

Conditions		Product	% Conversion
Temperature	CO_2 Pressure		
250°C.	250#	—	0
250°	500#	—	0
275°	250#	Beidellite	5
300°	250#	Beidellite	20
300°	500#	Beidellite	20
350°	250#	—	0
350°	500#	—	0

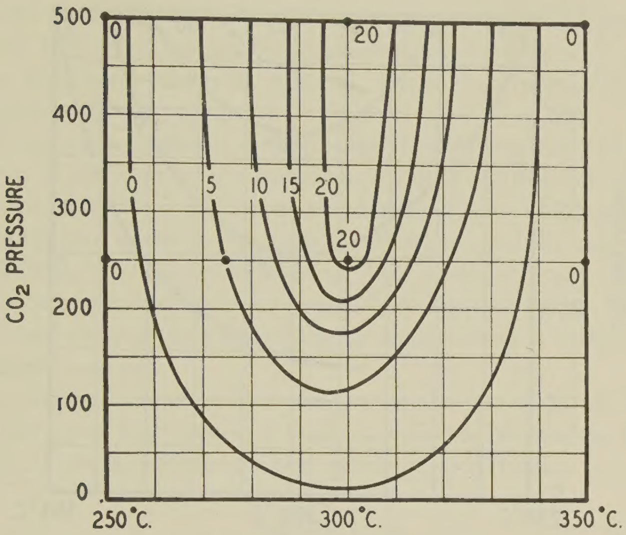

FIG. 1. Conversion of Albite.

NEPHELITE

The rate of conversion of this mineral is shown in Table 4 and Fig. 2. The rate is comparatively rapid over a large area, showing it is readily broken down. It is interesting to note the definite change in end product at different temperature levels.

TABLE 4

Conditions		Product	% Conversion
Temperature	CO_2 Pressure		
250°C.	500#	Sericite	20
275°	500#	Sericite	50
300°	250#	Sericite	20
300°	500#	Gibbsite	80
300°	375#	Sericite	40
325°	500#	Sericite	50
350°	250#	No change	0
350°	500#	No change	0

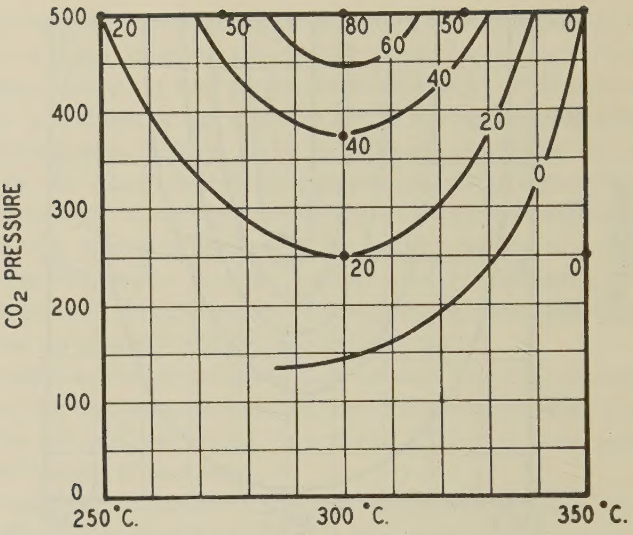

Fig. 2. Conversion of Nephelite.

The x-ray pattern for the 300°C. mineral is similar to that of gibbsite. Yet strangely enough the thermal curve (Fig. 3) is not exactly that of gibbsite, but approaches that of the monohydrate, diaspore. The small peak at 280°C. however corresponds to that of gibbsite.

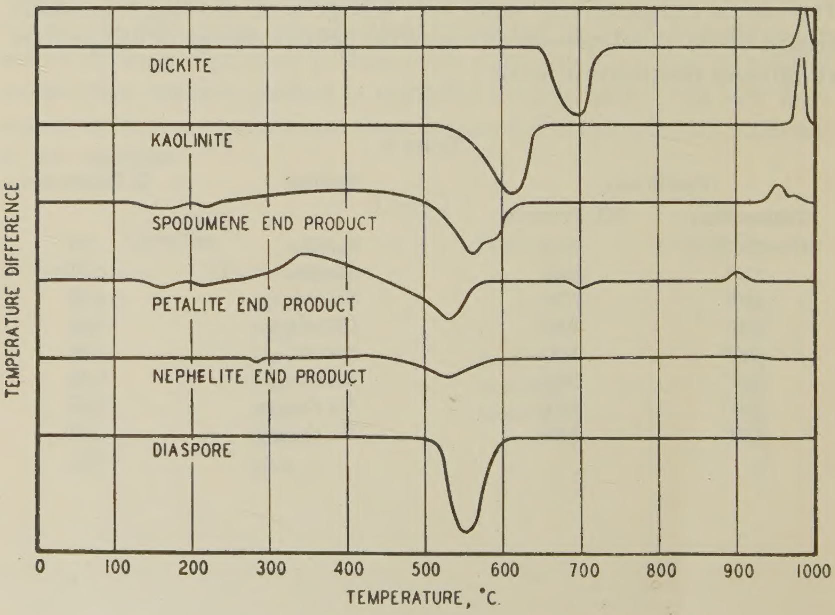

Fig. 3. Differential Thermal Curves.

A rough chemical analysis of this material gave 50% alumina, 22% silica and 22% of combined water, indicating a mixture of gibbsite or diaspore with some other clay mineral. The high alumina and combined water are significant.

Four runs were made on the nephelite at 300°C. and 500 pounds pressure. Two of the runs were carefully controlled so that the temperature never went more than 4°C. from the desired value. The other two runs had temperature variations of ±10°C. Only the carefully controlled runs gave gibbsite; the other gave sericite. This would indicate that we have probably missed other minerals in this investigation by not taking sufficiently close temperature intervals, or maintaining a sufficiently close temperature control.

There was no indication of a mixture of the two minerals; either one or the other was produced in a stable condition. No success was had in breaking up the sericite under hydrothermal conditions.

ORTHOCLASE

The rate of conversion for this mineral is shown in Table 5 and Fig. 4. The maximum rate comes at 300°C. and 500# CO_2 pressure. The equal rate lines go to higher pressures with lower temperatures. In regard to the nature of the end product, the *x*-ray pattern is similar to that of sericite, confirming the earlier results.

TABLE 5

Conditions		Product	% Conversion
Temperature	CO_2 Pressure		
250°C.	0#	—	0
250°	250#	—	0
250°	500#	—	0
275°	250#	—	0
300°	0#	—	0
300°	250#	Sericite	30
300°	500#	Sericite	70
325°	250#	Sericite	30
350°	0#	—	0
350°	250#	Sericite	20
350°	500#	—	0

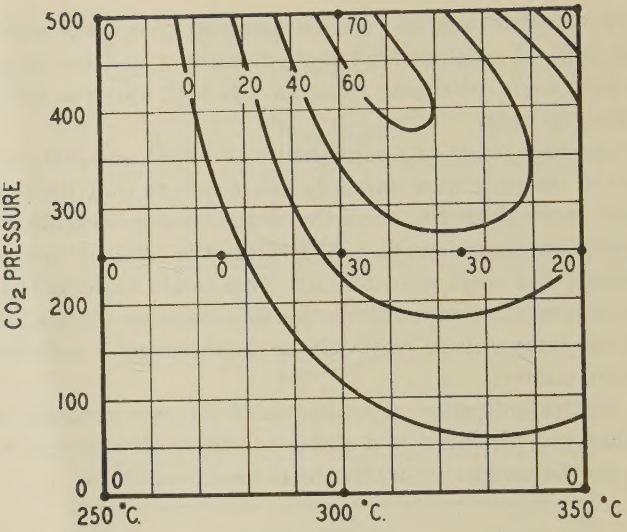

FIG. 4. Conversion of Orthoclase.

LEUCITE

Only one run was made on this mineral at 300°C. and 500#/sq. in. CO_2 pressure, showing 80% conversion. The end product gave an *x*-ray pattern similar to that of sericite.

PETALITE

One run was made on this mineral at 300°C. and 250# CO_2 pressure giving a conversion of 50%. The end product gave an *x*-ray pattern similar to, but not identical with kaolinite. A thermal curve for this mineral (Fig. 3) is somewhat like kaolinite, although the peaks are not as high as for kaolinite because of incomplete conversion. The small endothermic peak at 700°C. indicates that there is about 5% of dickite mixed with the kaolinite, an amount too small to be detected by the *x*-ray method. The irregularities in the initial part of the curve are due to the fine grain sizes, which also causes the low temperature of the exothermic peak.

SPODUMENE

The rate of conversion of this mineral is shown in Table 6 and Fig. 5, indicating a rather wide range of conditions for alteration. The end product gives the *x*-ray pattern of kaolinite. The chemical analysis of the nearly completely converted sample in Table 7 confirms this.

TABLE 6

Conditions		Product	% Conversion
Temperature	CO_2 Pressure		
250°C.	500#	Kaolinite	10
275°	250#	Kaolinite	50
300°	125#	Kaolinite	90
300°	250#	Kaolinite	90
300°	500#	Kaolinite	100
300°	0#	Kaolinite	90
325°	250#	Kaolinite	80
350°	250#	No change	0
350°	500#	No change	0

TABLE 7

Constituent	Spodumene (Thero.)	Kaolinite (Thero.)	End Product
SiO_2	64.5%	46.5%	48.4%
Al_2O_3	27.4	39.6	40.3
H_2O (Combined)	0.0	13.9	11.3
Li_2O	8.4	—	—

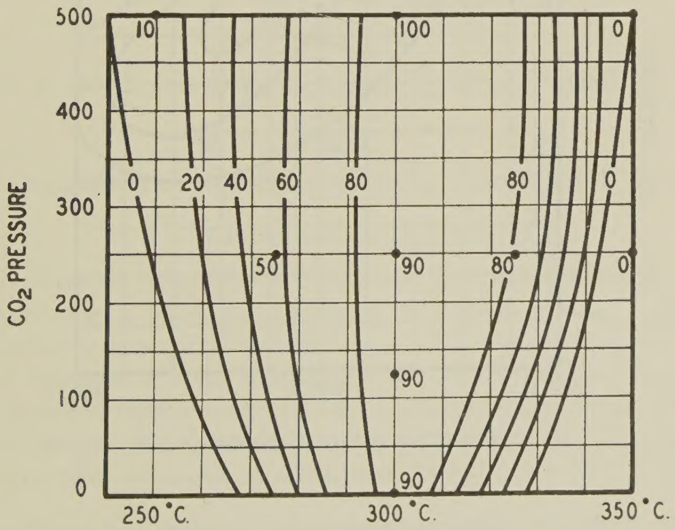

FIG. 5. Conversion of Spodumene.

The thermal curve of the end product (Fig. 3) is quite similar to that of fine grained kaolinite but the double endothermic peak would indicate that some diaspore was mixed with it.

ANORTHITE

The rates of conversion for this mineral are shown in Table 9 and Fig. 6, indicating about the same stability as orthoclase. The *x*-ray analysis shows that the end product consists of a mineral very like pyrophyllite. Unfortunately pyrophyllite does not give a characteristic thermal curve, so it cannot be checked in that way. A chemical analysis of the end product gave the following results.

TABLE 8

Constituent	Anorthite	Pyrophyllite	End Product
SiO_2	43.2%	66.7%	59.1%
Al_2O_3	36.7	28.3	21.9
H_2O	—	5.0	8.3
CaO	20.1	—	11.1

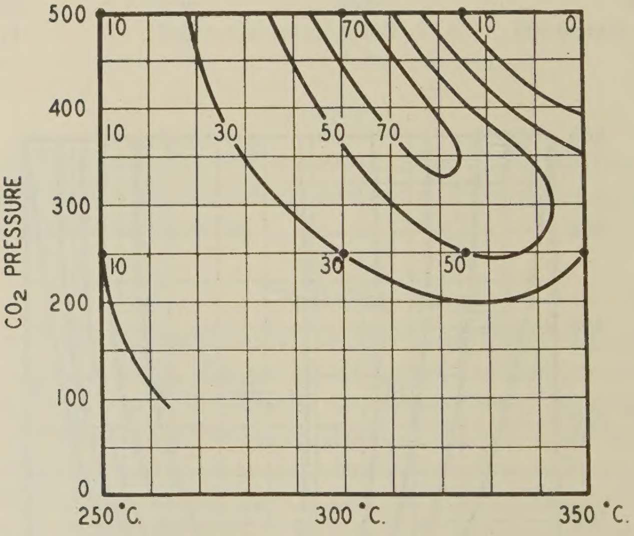

FIG. 6. Conversion of Anorthite.

The lime comes from some undecomposed anorthite and possibly some calcium silicate. In the latter case this would account for the excess silica in the end product.

These results are in agreement with the previous work on this mineral, but it is perhaps not justified in stating that the end product is identical with natural pyrophyllite, although it is very similar to it.

TABLE 9

Conditions		Product	% Conversion
Temperature	CO_2 Pressure		
250°C.	250#	Pyrophyllite	10
250°	500#	Pyrophyllite	10
275°	250#	Pyrophyllite	10
300°	250#	Pyrophyllite	30
300°	500#	Pyrophyllite	90
325°	250#	Pyrophyllite	50
350°	250#	Pyrophyllite	30
350°	500#	No change	0

POLLUCITE

One run was made on this mineral at 500# CO_2 pressure and 300°C. but no change was noted under these particular conditions. Unlike most of the other minerals tested, this one contains a molecule of water which undoubtedly increases its stability.

KAOLINITE

One run was made on this material at 500# CO_2 pressure and 300°C. which indicated no change, a result which would be expected.

LEPIDOLITE

A run at 300°C. and 500# CO_2 pressure gave no change.

BERYL

A run at 300°C. and 500# CO_2 pressure gave no change.

DISCUSSION OF RESULTS

A summary of the results is shown in Table 10 which brings out the fact that under a particular condition of temperature and acidity the end product is determined by the cation or the crystal structure of the original minerals, or some other factor associated with the parent mineral. These end products are not only different minerals, but belong to different groups. While the identity of some of the specific minerals is not too certain, the group to which they belong seems well established.

TABLE 10. SUMMARY OF REACTIONS

Parent Mineral	Formula	End Product	Temp. of Max. rate	Conversion in 320 hrs.
Albite	$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$	Beidellite	300°C.	25%
Nephelite	$Na_2O \cdot Al_2O_3 \cdot 2SiO_2$	Gibbsite, Sericite	300	80
Orthoclase	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	Sericite	300	75
Leucite	$K_2O \cdot Al_2O_3 \cdot 4SiO_2$	Sericite	300	80

Petalite	$Li_2O \cdot Al_2O_3 \cdot 8SiO_2$	Kaolinite	300	50
Spodumene	$Li_2O \cdot Al_2O_3 \cdot 4SiO_2$	Kaolinite	300	100
Lepidolite	$Li_2O \cdot 2Al_2O_3 \cdot K_2O \cdot 6SiO_2 \cdot 2H_2O$	No change	—	0
Anorthite	$CaO \cdot Al_2O_3 \cdot 2SiO_2$	Pyrophyllite	300	90
Beryl	$3BeO \cdot Al_2O_3 \cdot 6SiO_2$	No change	—	0
Pollucite	$2Cs_2O \cdot 2Al_2O_3 \cdot 9SiO_2 \cdot H_2O$	No change	—	0
Kaolinite	$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	No change	—	0

What are the determining factors that cause a certain clay mineral to form under hydrothermal conditions? There seems to be no evidence in nature that the clay minerals are determined by the cations in the parent rock. Again there is ample evidence of kaolinite forming in nature, for example, from both albite and orthoclase. The answer is that kaolinite when formed from these parent minerals does so under conditions outside of the range of our experiments. These conditions may be at higher pressures and temperatures, or more likely lower temperatures and much longer times; or perhaps with some other acid forming agent such as HCl, F or SO_3.

Much work has been done on the formation of clay minerals from coprecipitated gels where the end product is mainly determined by the temperature and acidity, whereas here there is only one case indicating a change in the end product by varying these factors; and little positive evidence of a mixture of minerals in the end products.

Most geologists consider the formation of the clay minerals as a step by step process such as:

$$\text{orthoclase} \rightarrow \text{sericite} \rightarrow \text{kaolinite} \rightarrow \text{gibbsite}.$$

But here we have no evidence of any intermediate steps. The conversion goes directly to its final, stable state. If kaolinite is the stable end product of spodumene at a certain temperature and acidity, why does leucite go directly to sericite under the same conditions? Does the original mineral break down to silica and alumina gels which recombine to form the clay minerals? If so, why does the cation often seem to govern the final form of the end product?

There is considerable evidence to indicate that the materials with lower total alkali content are more stable. For example albite ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$) is more stable than nephelite ($Na_2O \cdot Al_2O_3 \cdot 2SiO_2$); and petalite ($Li_2O \cdot Al_2O_3 \cdot 8SiO_2$) is more stable than spodumene ($Li_2O \cdot Al_2O_3 \cdot 4SiO_2$). This is a result which might be expected.

One of the most interesting results is in the case of nephelite which at 500# CO_2 pressure and 300°C. goes almost completely to gibbsite, while at the same pressure and 275°C. or 325°C. the end product is sericite and no gibbsite appears in the x-ray pattern. This shows over what a narrow temperature range a particular mineral can form.

CONCLUSIONS

If it is justified to draw any conclusions at this stage of the work, the following tentative statements may be made:

(1) Under the test conditions where CO_2-charged water is allowed to percolate through the finely ground mineral, a maximum reaction rate is observed around 300°C. and at the highest pressure used, that is, 500#/sq. in. for all the parent minerals tried. Below 250°C. and above 350°C. the parent minerals all appeared stable.

(2) The end product, in most of these tests, is not determined solely by the pressure, temperature and acidity, but also by some characteristic of the parent mineral.

(3) The reaction proceeds at once to the final mineral. There is no evidence of any intermediate steps.

(4) There is little evidence to indicate that more than a single clay mineral is in the end product.

FURTHER WORK

Additional work should be carried out on other aluminum silicates to determine the nature of the end product. Some, like celsian, are difficult to obtain pure in nature and will have to be made up from melts. Also, runs should be made on mechanical mixtures of two minerals to see if two end products result. Runs on an isomorphic series of feldspars would also be of interest.

Reaction chambers of high temperatures alloys should be constructed in order to extend the pressure-temperature diagrams to higher values, where other end products may result. Also, other gases such as HCl, F and SO_3 should be tried, as they are believed to cause alteration in nature. Larger quantities of the end products should be prepared so that more positive identification can be made.

ACKNOWLEDGMENTS

This work has been made possible by the generosity of the Geological Society of America which has allotted funds to carry out this investigation. The author wishes to express his appreciation for this assistance. The careful laboratory work of Robert L. Green, who assisted with this problem, is gratefully acknowledged.

APPENDIX

The following tables give the spacing of the stronger lines from the *x*-ray patterns. These pictures were taken on a Debeye Scherrer camera of 57.2 cm. diameter with Cu $K\alpha$

radiation through an aluminum shield .003 inch thick. The figures are in centimeters on the film, and the numerals after them are the line intensity with 10 the strongest.

TABLE 11. ALBITE CONVERSION

Albite	Conversion Product	Beidellite
	1.01—4	.99—10
1.10—4	1.11—4	
1.28—4	1.28—2	
	1.35—4	1.32—3
1.43—10	1.42—10	
1.55—4	1.54—3	
1.78—2	1.78—4	1.76—5 1.83—2
1.88—2	1.90—2	
2.16—2	2.18—1	
2.54—5	2.53—4	
2.78—2	2.78—2	2.73—2
	3.13—3	3.12—6
3.20—2		
3.31—2	3.30—2	
3.44—2	3.44—3	
3.52—2	3.51—2	
3.77—1	3.75—1	3.70—2
		3.83—2

TABLE 12. NEPHELITE CONVERSION

Nephelite	Conversion Product	Gibbsite
	.69—8	.71—8
	.77—8	.90—10
	1.02—3	1.01—6
1.20—2		
1.41—10	1.43—10	1.41—8
1.54—4		
1.73—2	1.73—5 1.82—5	
1.95—2	1.94—9	1.90—8
2.16		
2.46—2	2.49—10	2.45—8
2.56—3		
2.72—1	2.80—5	2.74—6
2.99—2	3.10—2 3.16—2	3.19—3
3.23—2	3.27—5	3.31—3
3.32—2		
3.43—2	3.42—3	
	3.65—6	3.60—4
3.75		

Table 13. Orthoclase Conversion

Orthoclase	Conversion Product	Sericite
1.06—1	1.08—2	1.00—8
1.29—½	1.31—2	
1.39—10	1.37—10	1.35—5
	1.42—10	1.39—5
1.55—4		
	1.75—2	1.79—10
	1.88—½	1.91—3
2.11—1	2.13—3	2.14—3
	2.16—½	2.19—2
2.56—5	2.55—5	
	2.57—5	
	2.82—½	2.80—2 2.84—2
	3.10—½	3.08—5
	3.18—1	3.14—5
	3.43—2	
	3.70 —½	3.68—3

Table 14. Leucite Conversion

Leucite	Conversion Product	Sericite
	.75—2	
.88—5	.84—2	
.95—1	1.00—7	1.00—8
1.35—10 (V. Broad)	1.35—2	1.35—5
	1.46—2	1.39—5
1.60—8		
1.71—2	1.71—10 1.79—10	1.79—10
	1.88—2	1.91—3
1.94—4		
2.05—3	2.05—2 (V. Broad)	2.14—3
	2.28—2(Broad)	2.19—2
2.60—1		
2.70—1		
2.80—3	2.80—3 (V. Broad)	2.80—2 2.84—2
2.89—1		
2.95—1		
3.05—1	3.09—8	3.08—5
3.16—1	3.15—8	3.14—5
3.45—1	3.50—1 (V. Broad)	
3.60—1		
3.66—1		
	3.70—3	3.68—3
3.85—1	3.85—1	

TABLE 15. PETALITE CONVERSION

Petalite	Conversion Product	Kaolinite
	1.03—6	.98—8 1.03—8
1.22—10	1.30—4	1.23—5
1.34—5	1.38—1	
1.41—5		
1.48—2		
1.58—2	1.62—1	
1.73—1		
1.83—2	1.84—7	1.74—8
1.90—1		
	1.97—3	1.89—10
2.04—1	2.09—1	
2.28—2	2.34—4	2.23—2
		2.52—1
2.60—1	2.61—1	
2.75—1	2.81—3	2.72—7
2.84—1		
2.91—2		
3.09—1		3.06—5
	3.19—9	3.14—1
3.23—2		
3.31—2		
3.42—1		
3.50—2	3.50—1	3.45—1
	3.77—2	3.76—3
3.90—1	3.93—2	3.90—1
3.98—1		
4.04—1		

TABLE 16. SPODUMENE CONVERSION

Spodumene	Conversion Product	Kaolinite
	1.02—8	.98—8 1.03—8
1.30—10	1.30—5	1.23—5
1.42—4		
	1.80—10	1.74—8
2.01—4	1.95—10	1.89—10
2.19—3	2.33—5	2.23—2
2.47—8		2.52—1
2.56—1		
2.84—4	2.80—5	2.72—7
3.06—3	3.02—1	3.06—5
	3.14—10	3.14—1
3.26—2		
3.31—1		
3.39—1		

3.45—2	3.45—½	3.45—1
3.54—1		
3.60—1	3.61—2	3.61—2
3.77—1	3.71—2	3.76—3
3.89—4	3.90—2	3.90—1
3.96—1		
4.07—1		
4.31—1		
4.71—1		
4.86—1	4.90—1	
4.96—1		

TABLE 17. ANORTHITE CONVERSION

Anorthite	Conversion Product	Pyrophyllite
		.73—4
		.82—4
	1.02—8	.98—10
1.34—10		
1.42—2	1.41—5	1.44—8
	1.79—8 (Broad)	1.74—4 1.83—4
	2.03—1	2.07—2
	2.16—2	2.16—2
2.53—3	2.58—2	
	2.76—2	2.75—2
3.03—2	3.06—2	
	3.14—4	3.12—3
3.43—4		
	3.49—4	3.47—2

OLIVINES FROM THE SKAERGAARD INTRUSION, KANGERDLUGSSUAK, EAST GREENLAND

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AND

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Four olivines separated from the rocks of the Skaergaard intrusion,[1] Kangerdlugssuak, East Greenland, have been analysed. The olivines occur in a layered gabbro intrusion which shows continuous crystallisation-differentiation from a lower and earlier hypersthene-olivine-gabbro to an upper and later fayalite-quartz-gabbro. Two of the three main constituents of this differentiation series, namely plagioclase and monoclinic pyroxene, show a continuous variation in composition, the plagioclase from medium labradorite to oligoclase-andesine, and the monoclinic pyroxene from a diopside-augite to a member of the hedenbergite-clinoferrosilite solid solution series.[2] Hypersthene is also an important constituent of the earlier rocks of the intrusion and varies from Fs_{41} in the lowest exposed rocks to at least Fs_{60} in rock 2000 m. up; above this it does not occur as separate crystals. Olivine is not found throughout the intrusion being absent for 500 metres at about the middle of the layered series. The olivines in the lower and earlier part of the layered series, of which I is an example, are in equilibrium with labradorite, a common type of pyroxene and hypersthene with about 40% $FeSiO_3$. The olivines of the second crystallisation period, of which II, III and IV are examples, are in equilibrium with andesine, an unusual iron-rich pyroxene, which we have already described, and quartz. In these upper rocks the iron-rich olivine was among the later minerals to crystallise, while in the lower and earlier rocks of the intrusion the more magnesian olivine, as is usual, was an early mineral. Except close to the olivine free horizon the amount of modal olivine in the average rock is never less than 10% and rarely greater than 20%.

The four olivines were first separated with the help of methylene iodide, and clerici solutions. They were further purified by an electromagnet and then by hand picking. Olivines I, II and III were practically free from inclusions, but IV contained a large number of minute orientated crystals of iron ore. These were removed by gelatinising the olivine with dilute hydrochloric acid, separating the solution from the silica and

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[1] Wager, L. R., Geological Investigations in East Greenland, Part I. Meddl. om. Gronland, vol. **105**, no. 2, pp. 36–37, 1934.

[2] Deer, W. A., and Wager, L. R., Two new pyroxenes included in the system clinoenstatite, clinoferrosilite, diopside and hedenbergite: *Min. Mag.*, vol. **25**, pp. 15–22, 1938.

TABLE 1

	Olivine I				Olivine II			
	Wt. %	Mol. %	Atomic ratio to 4 oxygens		Wt. %	Mol. %	Atomic ratio to 4 oxygens	
SiO_2	38.11	0.6345	1.028		33.72	0.5614	1.006	
Al_2O_3	nil	—	—		nil	—	—	
TiO_2	trace	—	—		trace	—	—	
Fe_2O_3	0.15	0.0009	0.003		0.05	0.0003	0.002	
FeO	31.48	0.4382	0.710	1.94	47.91	0.6669	1.190	2.00
MnO	0.22	0.0031	0.004		0.41	0.0058	0.010	
MgO	30.50	0.7564	1.225		18.07	0.4482	0.799	
CaO	0.02	—	—		nil	—	—	
	100.48				100.16			
		$(Mg, Fe, Mn)_2[SiO_4]$ $Fo_{64}Fa_{36}$				$(Mg, Fe, Mn)_2[SiO_4]$ $Fo_{41}Fa_{59}$		
		Olivine III				Olivine IV		
SiO_2	31.85	0.5303	1.008		30.15	0.5019	1.002	
Al_2O_3	trace	—	—		0.07	0.0007	.003	
TiO_2	0.01	—	—		0.20	0.0025	.006	
Fe_2O_3	0.11	0.0007	0.003		0.43	0.0027	.010	
FeO	58.64	0.8162	1.552	1.98	65.02	0.9049	1.807	1.99
MnO	0.85	0.0120	0.023		1.01	0.0149	.030	
MgO	8.49	0.2105	0.400		1.05	0.0260	.052	
CaO	0.18	0.0032	0.006		2.18	0.0389	.078	
	100.13				100.11			
		$(Mg, Fe, Mn, Ca)_2[SiO_4]$ $Fo_{20}Fa_{80}$				$(Mg, Fe, Mn, Ca)_2[SiO_4]$ Fo_3Fa_{97}		

inclusions, and finally separating the gelatinous silica from the ore inclusions.

The refractive indices of the olivines were determined by the immersion method using a series of liquids with high dispersion. For those olivines with refractive indices between 1.735 and 1.770 a solution of sulphur in methylene iodide was used, for those between 1.770 and 1.852 two solutions, one of equal parts and one of three parts phenyldi-iodoarsine[3] ($C_6H_5AsI_2$) and one part methylene iodide, and for those above 1.852, pure phenyldi-iodoarsine. The refractive indices of these liquids for varying wave lengths were obtained by placing them in a small hollow 30° prism on a single circle Fuess goniometer and using the minimum deviation method. As a convenient method of obtaining monochromatic light of varying wave lengths, a monochromatic illuminator designed by Tutton[4] was used, the source of the light being a liliput arc. The monochromator was standardised with yellow sodium light and yellow, green and violet light from a mercury vapour lamp. From a large number of readings, graphs giving the full dispersion of the liquids, were drawn. The measurements of the optic axial angle were made on a universal stage and the specific gravities were determined by suspension in clerici solutions diluted with water, the specific gravity of the solutions being obtained with a hydrostatic balance.

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[3] Anderson, B. W., and Payne, C. J., Liquids of high refractive index: *Nature*, London, vol. **133**, pp. 66–67, 1934. Also, The refractometer and other refractive index methods: *Gemnologist*, London, vol. **3**, pp. 216–227, 1934.

TABLE 2

		I	II	III	IV
2V (negative).[1]		79°	65°	58°	48°
Refractive indices.[2]	α	1.710	1.752	1.788	1.827
	β	1.733	1.781	1.828	1.869
	γ	1.748	1.795	1.840	1.879
	$\gamma-\alpha$	0.038	0.043	0.052	0.052
Colour in thin section.		Faint yellow.	Pale yellowish amber.		Yellowish amber.
Pleochroism.		As for IV but less, corresponding to colour.			$\alpha=\gamma$ pale yellow. $\beta=$orange yellow.
Colour as small grains.		Lemon yellow.	Deep amber.		Deep reddish brown.[3]
Specific gravity.		3.69	3.88	4.15	n.d.

[1] Determinations ± 2°.
[2] Determination ± .002.
[3] Partly the result of ore inclusions.

The optical data are given in Table 2 and have been plotted also against chemical composition, and superimposed on the refractive index diagram for the synthetic Mg-Fe olivines of Bowen and Schairer[5] (Fig. 1). For the natural olivines the small amounts of impurities have been disregarded and the analyses recalculated in terms of Mg_2SiO_4 and Fe_2SiO_4. The refractive index of the natural minerals is in every case a little higher than that of the artificial, but the agreement is close. There is also close agreement, except at the fayalite end, with the refractive index curves drawn by Winchell[6] from the less complete series of natural minerals previously known.

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[4] Tutton, A. E. H., Crystallography and Practical Crystal Measurement, *London*, vol. **2**, pp. 959–965, 1922.

[5] Bowen, N. L., and Schairer, J. F., The system, $MgO\text{-}FeO\text{-}SiO_2$: *Am. Jour. Sci.*, vol. **29**, p. 197, 1935.

Besides the physical properties given in Table 2 mention should be made of the cleavage and inclusions. The iron rich olivine II has distinct cleavages parallel to [010]. Tabular inclusions of ore are abundant parallel to [100] and are sporadic parallel to [001]. This olivine is comparable with the Onverwacht hortonolite[7] from the Bushveld Complex in which very distinct [010] and less distinct [001] cleavages are developed. The Bushveld mineral also has two sets of included minute tabular plates lying at right angles to each other and developed in sheets parallel to [100] and [001]. The refractive index β is 1.749 ($=Fo_{52}Fa_{48}$) compared with 1.781 ($=Fo_{41}Fa_{59}$) for the Skaergaard hortonolite. The more iron rich olivines, III and IV, have similar cleavages and more abundant inclusions.

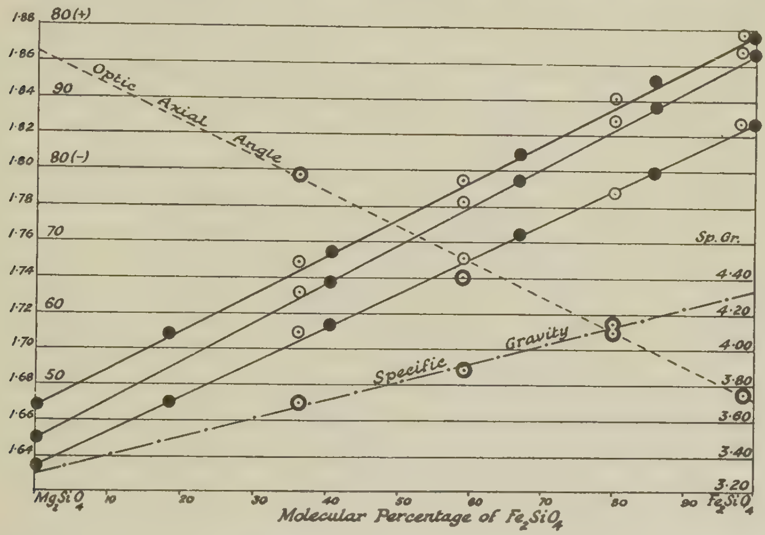

FIG. 1. Variations in composition and optical properties of the olivine series. ● Variation of refractive indices after Bowen and Schairer. ⊙ Date for the olivines of the Skaergaard intrusion.

Olivines containing from 0 to 30 molecular percentage of Fe_2SiO_4 are common in igneous rocks, and olivines with as much as 50% Fa are known and have been described from a number of localities, especially from the Bushveld Complex,[8] the East Greenland basalts north of

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[6] Winchell, A. N., Elements of Optical Mineralogy, *New York*, Pt. 2, p. 191, 1933.

[7] Wagner, P. A., Platinum Deposits and Mines of South Africa: *London*, pp. 55–59, 1929.

[8] Wagner, P. A., *op. cit.*, pp. 50–68.

Scoresby Sound,[9] and the Hällefors Dyke.[10] Fayalite is of course well known as a natural mineral. Although recently the complete series of solid solution from Mg_2SiO_4 to Fe_2SiO_4 have been synthesised and described, the complete series had not previously been found to occur naturally. The two iron rich olivines II and III, are therefore, of immediate interest for they extend the range of naturally occurring olivines and, in conjunction with other examples from the Skaergaard intrusion, prove that in natural magmas, as in the laboratory, a complete series of solid solutions may occur. In Table 3 the analyses of the Kangerdlugssuak olivines are compared with analyses of other iron rich olivines. The previously existing gap in our knowledge of natural olivines was between those containing 50% fayalite and almost pure fayalite.

Although olivines II, III and IV have crystallised from a magma comparatively rich in lime, they have remained almost pure members of the simple solid solution series Mg_2SiO_4-Fe_2SiO_4 being with the exception of IV practically free from Ca_2SiO_4. In this respect they resemble fayalites from syenites which are also apparently free from Ca_2SiO_4 although there is plenty of lime in the rocks from which they come. The fayalites from lithophysae and acid lavas are also lime free but this is to be expected as they have crystallised from a magma poor in both lime and magnesia. It is interesting to find that these natural iron rich olivines are also free from lime in view of the results from the synthetic melt system CaO-FeO-SiO_2.[11] Olivine IV is in equilibrium with a monoclinic pyroxene of the hedenbergite-clinoferrosilite solid solution series, close to ($Wo_{30}En_1Fe_{69}$) in composition, with plagioclase, Ab_{70}, and quartz. The data from the synthetic system suggest that olivine in equilibrium with a similar monoclinic pyroxene, excluding the 1% of $MgSiO_3$, would contain between 6 and 7% Ca_2SiO_4. As we have stated above there is no lack of lime in the rock and we can offer no definite explanation of this difference from the experimentally determined system. The percentage of Mn_2SiO_4 is also low but this is to be expected as the rocks are relatively poor in manganese. It is, however, significant that as the manganese content of the rocks increases the manganese in the olivines also increases.

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[9] Backlund, H. G., and Malmquist, D., Zur Geologie und Petrographie der Nordostgronlandischen Basaltformation. Part 1, Die Basische Reiche. Meddel om Gronland, vol. **87**, part 5, pp. 1–61, 1932.

[10] Krokström, T., The Hällefors dolerite dyke and some problems of basaltic rocks: *Bull. Geol. Instit. Upsala*, vol. **26**, pp. 115–258, 1936.

[11] Bowen, N. L., Schairer, J. F., and Posnjak, E., The system, CaO-FeO-SiO_2: *Am. Jour. Sci.*, vol. **26**, p. 233, 1933.

The four analysed olivines form a comparatively pure mineral series thus contrasting with the variations found in the pyroxene series (Deer and Wager 1938). This may be related to the simpler unit cell of the olivines giving less possibilities for variation. As there is no replacement of silicon by aluminium in the independent SiO_4 tetrahedra, the replacement of divalent Mg, Fe and Mn by trivalent iron and alumina or tetravalent titania does not take place and the olivines have a relatively simple composition.

TABLE 3. ANALYSES OF IRON-RICH OLIVINES AND DUNITES

	A	B	I	C	D	E	II	F	III	IV	G
SiO_2	37.92	36.72	38.11	34.00	34.38	33.94	33.72	33.27	31.85	30.15	29.60
Al_2O_3	—	—	nil	—	1.46	—	nil	—	trace	0.07	—
TiO_2	—	—	trace	nil	0.05	—	trace	trace	0.01	0.20	—
Fe_2O_3	—	—	0.15	—	0.03	—	0.05	0.37	0.11	0.43	—
FeO	25.96	29.96	31.48	37.80	38.30	47.32	47.91	49.32	58.64	65.02	68.73
MnO	—	—	0.22	—	0.40	4.32	0.41	1.50	0.85	1.01	—
MgO	34.47	31.99	30.50	23.60	22.09	13.74	18.07	16.08	8.49	1.05	1.78
CaO	nil	nil	0.02	—	2.36	—	nil	—	0.18	2.18	—
H_2O	—	—	—	—	0.55	0.48	—	—	—	—	—
	98.35	98.67	100.48	95.40	99.62	99.80	100.16	100.54	100.13	100.11	100.11

A. Dunite composed of iron-rich olivine, approaching hyalosiderite, from Upper Quarry, Driekop Mine. Anal. A. MacJohnson (Wagner, **1929**, p. 84).

B. Hyalosiderite. Kaiserstuhl (Doelter, vol. **2**, p. 1, p. 300).

I. Hyalosiderite. E.G.4077, from hypersthene-hyalosiderite-gabbro, Kangerdlugssuak, E. Greenland.

C. Honey-brown, coarse-grained hortonolite-dunite 200 ft. level, Onverwacht Mine. Anal. R. A. Cooper (Wagner, **1929**, p. 60) (incomplete analysis).

D. Hortonolite-dunite from outcrop, Onverwacht Mine, Lydenberg District, Transvaal. Anal. H. G. Weall (Wagner, **1929**. p. 60). Recalculated analysis which showed 2.90% Fe_2O_3 on assumption that all ferric oxide except 0.05% of magnetite, originally present as ferrous oxide. Analysis includes Cr_2O_3, 0.10; Na_2O, 0.20; P_2O_5, 0.05.

E. Hortonolite, Munroe, Orange Co., N. J. (Penfield and Forbes, **1896**, p. 211).

II. Hortonolite, E.G.1907, from quartz-hortonolite-gabbro. Kangerdlugssuak, E. Greenland.

F. Hortonolite. Cumberland (Rhode Island). (Anal. C. H. Warren, 1908.)

III. Ferrohortonolite, E.G.4146, from quartz-ferrohortonolite-gabbro. Kangerdlugssuak, E. Greenland.

IV. Fayalite, E.G.4139, from quartz-fayalite-gabbro. Kangerdlugssuak, E. Greenland.

G. Fayalite from pegmatite, Mourne Mts., Ireland. Quoted from Doelter, vol. **2**, pt. 1, p. 716.

Analyst for olivines I–IV, W. A. Deer.

At present the classification of the olivine series is somewhat confused and there is a considerable lack of agreement about the subdivisions and their names. Wagner[12] has stated: "the term olivine, by general consent, is applied to mixtures of forsterite and fayalite having the constitution $n\mathrm{Mg_2SiO_4}+\mathrm{Fe_2SiO_4}$ where n varies from 12 to 2." In using the name olivine for a definite part of the series Wagner followed Dana[13] and Iddings,[14] although the latter (p. 46) states that in common olivines the FeO% may reach 12 (i.e. $=Fo_{87}Fa_{13}$) and in another place[15] he uses olivine as the group name and both olivine and chrysolite for compositions between forsterite and hortonolite. Mügge[16] in his revision of Rosenbusch, Miers,[17] Niggli,[18] Winchell[19] and Alling[20] and many others use olivine as the group name. No agreement exists moreover, in the names of the subdivisions of the series. Winchell[21] restricts the name chrysolite to minerals containing between 5 and 25% Fe_2SiO_4, and Alling to minerals between 15 and 35% Mg_2SiO_4. Wagner uses the name hyalosiderite, following Hintz[22] and Doelter,[23] for minerals "in which the ratio of Mg_2SiO_4 to Fe_2SiO_4 is approximately as 2:1," and he states that the name should only be applied to varieties of the mineral having that composition. Alling proposes 65 to 40% Mg_2SiO_4 as the limits for hyalosiderite and thus encroaches on Wagner's definition of the term hortonolite.

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[12] Wagner, *op. cit.*, pp. 50–51.

[13] Dana, E. S., A Textbook of Mineralogy, *New York*, pp. 510–13, **1922.**

[14] Iddings, J. P., Igneous Rocks, *New York*, vol. 1, pp. 44, 46, **1909.**

[15] Iddings, J. P., Rock Minerals, *New York*, pp. 379–86, **1911.**

The authors consider that if separate names are to be used for various parts of the continuous series of solid solutions of Mg_2SiO_4 and Fe_2SiO_4 that the subdivision should be systematic. At present the names commonly accepted, in order of increasing richness in the fayalite molecule are forsterite, chrysolite, hyalosiderite, hortonolite and fayalite. Although Winchell uses these terms he refrains from defining the limits of hortonolite. Wagner accepted all these names except chrysolite, and Alling in dealing recently with the classification of the olivines used all the names. The two latter authors suggested definite limits but the range of their subdivisions is different. The end members, forsterite and fayalite have been variously defined, from 5 to 15%, leaving 90 or 70% of the series to be covered by three names, and in each case an unequal subdivision of the middle of the series was made. In view of the fact that naturally occurring olivines have now been shown to range over the whole series it is important that the nomenclature should be standardised. This we believe can be done without undue modification of the previous schemes and yet in a way which will systematise the subdivision. Thus if the names forsterite and fayalite are limited to olivines having from between 0 to 10, and 90 to 100 molecular per cent of Fe_2SiO_4, respectively, then the series may be divided systematically into units with a range of 20%. Such a subdivision which is like that of the plagioclase series is compared with some of the previously suggested classifications in Fig. 2. The existing names can satisfactorily be adapted for these subdivisions except that from 70 to 90% Fa is without any name. For this we suggest the compound name ferrohortonolite.

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[16] Mügge, O., Mikroskopische Physiographie der Petrographisch Wichtigen Mineralien by H. Rosenbusch, vol. **1,** part 11, pp. 354–67, 1927.

[17] Miers, A. A., Mineralogy, *London,* pp. 414–16, **1902.**

[18] Niggli, P., Lehrbuch der Mineralogie, *Berlin,* vol. **11,** pp. 521–26, 1926.

[19] Winchell, A. N., *op. cit.,* pp. 186–94.

[20] Alling, H. L., Interpretative Petrology of the Igneous Rocks, *New York,* p. 105, **1936.**

[21] Winchell, A. N., The Microscopic Characters of Artificial Minerals, *New York,* p. 291, **1931.**

[22] Hintze, Handbuch der Mineralogie, vol. **2,** p. 22, 1897.

[23] Doelter, Handbuch der Mineralchemie, vol. **2,** pl. 1, pp. 289–313, 1914.

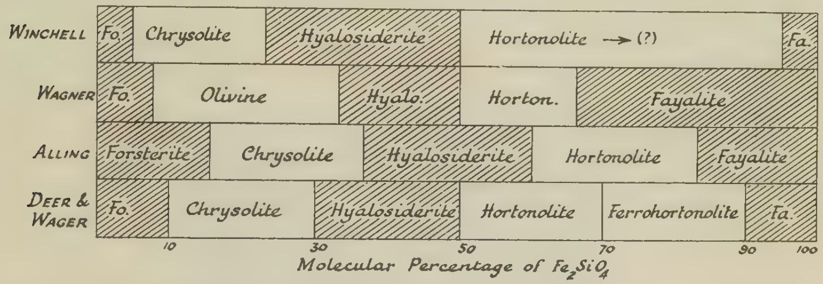

FIG. 2. Proposed classification of the Mg_2SiO_4-Fe_2SiO_4 olivines compared with the subdivisions of Winchell, Wagner and Alling.

The new data from these Kangerdlugssuak olivines show that the composition of natural olivines may be estimated from measurement of the refractive indices or of 2V. If more accurate determinations be made of the composition of olivines than has been the practice of most petrologists in the past, a far greater range than at present suspected may well be found among the common igneous rocks.

INESITE*

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CONTENTS

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Chemical composition of inesite
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ABSTRACT

Inesite, a hydrous manganese, calcium silicate from Quinault, Washington, a new locality for that mineral, has been analyzed and the optical properties determined. For purposes of comparison, the optical properties of inesite from eight other localities have been redetermined and the chemical analyses compiled. These all show close agreement in optical properties, and chemical composition with the inesite from Quinault. The maximum variation of indices of refraction is 0.005, and agrees with the uniformity in chemical composition. The average indices of refraction of inesite are: $\alpha = 1.616$, $\beta = 1.640$, $\gamma = 1.651$.

The analyses do not agree with the commonly accepted simple formulas. Calcium is present in fixed quantity and does not vary reciprocally with manganese, as it does in rhodonite. No simple formula could be determined for inesite. The most probable formula seems to be the complex one $15SiO_2 \cdot 3CaO \cdot 11MnO \cdot 10H_2O$.

INESITE FROM QUINAULT, WASHINGTON

Introduction

A small specimen of radiating, flesh-colored inesite, a hydrous silicate of manganese and calcium, was obtained by Mr. J. T. Pardee, geologist of the United States Geological Survey, from Mr. Ed Brooks of Piedmont (Crescent Lake), Oregon. Mr. Brooks stated that the sample came from Quinault, on the southwestern slope of the Olympic Mountains in the northern part of the state of Washington. The specimen, although only 3½ centimeters in diameter, contains an unusually pure seam of inesite about 2 centimeters wide and constitutes about two-thirds of the specimen. It is shown, slightly enlarged, in Fig. 1.

The study of the specimens, the determination of the optical properties, and the compilation of published data on inesite were made by one author (J. J. G.); and the comparison of analyses, and the derivation of the chemical formula is the contribution of the other author (W. T. S.). The chemical analysis of the inesite from Quinault was made by J. G. Fairchild, and the spectrographic examination by George Steiger, both of the United States Geological Survey, to whom the authors are greatly indebted. The writers are also indebted to Professors Adolph Pabst, and N. F. Taliaferro, of the University of California, for the sample of inesite from Napa County, California, now deposited in the United States National Museum, and to Dr. W. F. Foshag, of the United States National Museum, through whose cooperation additional samples from various localities were secured.

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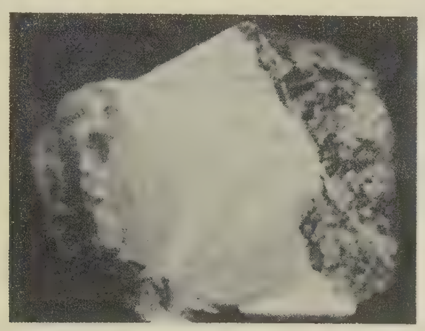

FIG. 1. Inesite from Quinault, Washington, showing the typical radial habit and the fiber-form of the crystals. The dark mineral is neotocite, and the thread-like veinlet is calcite. Slightly enlarged (4/3×).

Physical and optical properties

The inesite from Quinault occurs in flesh colored, radiating, slender laths, about a millimeter thick and 15 millimeters long, forming imperfect fan-shaped clusters. The vitreous to silky inesite is surrounded by dark liver-brown amorphous neotocite ($n=1.467$). Two cleavages, one visibly more perfect than the other, are present. On close inspection the laths show a lamellar habit giving the surface a striated appearance. Associated with the inesite is a thin crust of calcite between the ends of the laths and the surrounding neotocite.

The material used for optical determinations and chemical analysis was carefully hand picked from the purest portion of the specimen. The elongated lath-like plates commonly lie on the most perfect cleavage, $b\{010\}$, and are bounded on the edges by another nearly perfect cleavage, $a\{100\}$. The crushed fragments are colorless in transmitted light, and show no perceptible pleochroism.

Sections lying on the best cleavage, $b\{010\}$, show a nearly centered interference figure, negative, $2V=74°$. The dispersion of the optic axes is strong, $r>v$. Assuming the c axis to be parallel to the elongation,

$Z \wedge c = 29^\circ 30'$, $Y \wedge c = 60^\circ 30'$. Cleavage plates parallel to $a\{100\}$ show no interference figure, and extinguish 13° to 15° against the elongation. Polysynthetic twinning is occasionally seen on some of the pieces with low birefringence. The indices of refraction measured by the immersion method are: $\alpha = 1.616$, $\beta = 1.641$, $\gamma = 1.652$; ± 0.001.

Chemical composition

The chemical analysis of selected material is shown in the following table:

Table 1. Analysis and Molecular Ratios of Inesite from Quinault, Washington

[J. G. Fairchild, Analyst]

	Analysis	Molecular ratios			
SiO_2	45.67	0.7599		or 3.00	or 2.00
MnO	35.10	0.4951	0.6955	or 2.75	or 1.83
FeO	0.92	0.0128			
MgO	0.86	0.0213			
CaO	9.33	0.1663			
H_2O-	2.13	0.4778		or 1.89	or 1.26
H_2O+	6.53				
Al_2O_3, PbO	None				
	100.54				

These ratios do not yield any simple formula, and differ considerably from both of the commonly accepted formulas of inesite, namely $3SiO_2 \cdot 3RO \cdot 2H_2O$, and $2SiO_2 \cdot 2RO \cdot H_2O$. A study of published analyses was, therefore, undertaken and the results of a comparative study are given in a later section.

A spectrographic analysis of the inesite from Quinault, Washington, made by George Steiger, showed potassium and tin to be present in small quantities. The following elements are absent: Ba, Sr, Cs, Rb, Li, B, Ag, As, Bi, Pb, Sb, Zn, Be, Cd, Ge, and Tl. The mineral was placed directly in the arc, using graphite electrodes, and this method would detect quantities of from two or three hundredths of one per cent.

Optical Properties of Inesite

For the purpose of comparing the optical properties of inesite from Quinault, Washington, with those of inesite from other localities, five additional specimens from Rumania, Germany, two localities in Sweden, and Napa County, California, were also studied.

Nagybanya, Transylvania, Rumania (U.S.N.M. Cat. No. 103077). This specimen showed typical radiating laths of a very pale flesh color and a silky luster. The outward pointing laths terminate in a banded zone of chalcedonic, glassy white, and amethystine quartz. The central points from which the laths of inesite radiate have become altered to a light brown carbonate, apparently calcite, and only the long ends of the laths embedded in the quartz have retained their original character. (No. 8, Table 2.)

Nanzenbach, Nassau, Germany (U.S.N.M. Cat. No. 4003). Small fan-shaped clusters of radiating rose-colored laths of inesite are intergrown with snow-white calcite and embedded in a mass of dark liver-brown amorphous neotocite ($n=1.467$). The specimen closely resembles the one from Quinault, Washington, both in structure and in mineral association. (No. 9, Table 2.)

Pajsberg, Sweden (U.S.N.M. Cat. 51468). The specimen is composed largely of dark brown, compact, amorphous neotocite, with small aggregates of flesh-colored radiating laths of inesite. A little calcite is associated with the inesite along the boundary of the neotocite. (No. 10, Table 2.)

Långban, Sweden (U.S.N.M. Cat. No. 95306). This specimen exhibits the typical radial habit of inesite more strikingly than do most of the specimens studied. The flesh-colored inesite forms radiating clusters about $2\frac{1}{2}$ centimeters in diameter, embedded in white barite. Other associated minerals are amber-colored andradite ($n=1.895$); a brown-red mica-like mineral (manganophyllite?) resembling fine-grained muscovite ($2V=0°$ to $5°$, $\alpha=1.550$, $\beta=1.579$, $\gamma=1.580$, pleochroism strong, pale pinkish brown to brownish red); a little calcite; and a few grains of a black opaque, unidentified mineral. (No. 11, Table 2.)

Napa County, California (U.S.N.M. Cat. No. 103078). Pearly, lavender-pink aggregates of thin, radiating blades are clustered together in narrow, sheaf-like bundles about 2 centimeters long and from 1 to 1.5 millimeters wide. They are embedded in a matrix of compact, very fine-grained, dark brown bementite, resembling brown chert, having a mean index of refraction of 1.650. Thread-like veinlets of calcite cut through the bementite. (No. 12, Table 2.)

The optical determinations made on these five specimens, with those determined on the Quinault material, are given in Table 2, together with the data taken from the literature,[1] which are included for comparison.

Up to the time of the present study only a few quantitative determinations of the optical properties of inesite have been made. The few early

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[1] References are given at end of paper.

Table 2. Compilation of All of the Available Optical Data for Inesite from Various Localities

	I.			II.				III.						
	1	2	3	4	5	6	7	8	9	10	11	12	13	
Locality	Nanzenbach	Dillenberg	Pajsberg	Pajsberg	Banska, Slovak.	Idzu, Jap.	Hokkaido	Nagybanya	Nanzenbach	Pajsberg	Långban	Napa Co., Calif.	Quinault, Wash.	Average exclusive of doubtful data
Data by	Schneider	Schneider	Flink	Larsen	Ulrich	Kato	Yoshimura	Glass	Glass	Glass	Glass	Glass	Glass	
System	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl	Tricl
Cleavage	b, a	b, a	.....	.....	.....	.....	.....	b, a	b, a	b, a	b, a	b, a	b, a	b, a
α	.....	.....	.....	*1.609	1.618	1.617	*1.624	1.614	1.619	1.615	1.616	1.616	1.616	1.616
β	.....	.....	.....	*1.636	.....	1.640	1.643	1.638	1.642	1.640	1.640	1.641	1.641	1.640
γ	.....	.....	.....	*1.644	.....	.....	1.651	1.649	1.654	1.651	1.652	1.653	1.652	1.651
$\gamma-\alpha$	.....	.....	.....	0.035	.....	.....	*0.027	0.035	0.035	0.036	0.036	0.037	0.036	0.035
Sign	—	—	.....	—	—	—	—	—	—	—	—	—	—	—
2V	.....	*63°[a]	.....	*56°[b]	.....	Large	.....	74°	74°	75°	74°	75°	74°	74°
Disp.	$r>v$	$r>v$	.....	$r>v$	.....	.....	.....	$r>v$	$r>v$	$r>v$	$r>v$	$r>v$	$r>v$	$r>v$
Ext. on b(010) $Z\wedge c$	29°	60½°	30°	60°	.....	60°	.....	29°	30°	30°	29½°	33°	29½°	30°
Ext. on a(100)	.....	12°	15°	10°	.....	.....	.....	12°	12°	13°	13°	15°	13°	13°

I. Data by early investigators: 1, 2, 3

II. Data, some of which is doubtful or incomplete: 4, 5, 6, 7.

III. Data obtained from recent investigation by the writer: 8, 9, 10, 11, 12, 13.

* Doubtful data.

[a] Axial angle measured on cleavage fragments parallel to b: $2G_{a.y.}=63°28'$ Na (Adams polariscope with $n_y=1.7782$ Na for the glass).

[b] Value for 2V calculated from indices.

optical observations made on analyzed material are given in Table 2, Nos. 1, 2, and 3. Chemical analyses have been made on inesite from Nanzenbach, Germany, and from Pajsberg, Sweden, and optical determinations have been recorded on material from these two localities, but not on the analyzed material. Optical data and chemical analyses both made on the same material, are available from only two localities, namely, that from Idzu, Japan, and from Quinault, Washington.

The results of observations made by Schneider on the materials from Nanzenbach and Dillenberg, and by Flink on material from Pajsberg, show close agreement with the new data.

The indices of refraction determined by Larsen on inesite from Pajsberg (Table 2, No. 4) are apparently slightly low, and since the birefringence (0.035) is in accord with more recent data, it is probable that the index media were out of adjustment. The value for the α index found by Ulrich (Table 2, No. 5) is in agreement with the new data. This value, he asserts, was several times "confirmed" in an effort to match Larsen's lower (and apparently incorrect) value. Optical properties by Kato (Table 2, No. 6) on material from Idzu are in agreement with those newly determined. The value for α in Yoshimuri's determinations (Table 2, No. 7), is probably too high. The values for β and γ are in agreement with the data obtained in the present investigation.

The optical properties of inesite from the six localities studied (Table 2, Nos. 8, 9, 10, 11, 12, 13), are remarkably constant, the variations being but slightly greater than the errors of measurement. The uniformity of the optical data from nine different localities indicates a constant chemical composition for the mineral, a conclusion arrived at independently from a consideration of the available analyses. (See also Fig. 2.)

Chemical Composition of Inesite

The formula for inesite is commonly written $2(Mn,Ca)O \cdot 2SiO_2 \cdot H_2O$, although Schneider, the original describer, suggested $(Mn,Ca)(MnOH)_2$-$Si_3O_8 + H_2O$ or $3(Mn,Ca)O \cdot 3SiO_2 \cdot 2H_2O$. This last formula was adopted by Ford,[2] writing it $H_2(Mn,Ca)_6Si_6O_{19} \cdot 3H_2O$, following Farrington. Berman[3] writes the formula $(Ca,Mn)_3Si_3O_8(OH)_2$ or $3(Ca,Mn)O \cdot 3SiO_2 \cdot H_2O$, ignoring half the water, and suggesting a close relation, chemically, to xonotlite, $Ca_3Si_3O_8(OH)_2$. These formulas have a 1:1 ratio of silica to bases.

Previous writers have generally grouped the CaO with the MnO, as (Mn,Ca)O indicating a reciprocal variability of the CaO with MnO.

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[2] Ford, W. E., A Textbook of Mineralogy by E. S. Dana, 4th ed., p. 640, 1932.

[3] Berman, Harry, Constitution and classification of the natural silicates: *Am. Mineral.*, vol. **22**, pp. 360, 391, 1937.

Where these are written separately a ratio of MnO:CaO of 4:1 is general adopted. Fairchild's analysis of the inesite from Quinault gives a ratio of SiO_2:(MnO+CaO+FeO+MgO):H_2O of 3.00:2.75:1.89, with a marked deficiency in the bases for a 1:1 ratio to silica. As shown on the following pages, all analyses of inesite show a similar deficiency and in none of them is the ratio of SiO_2:RO equal to 1:1.

The compilation of available analyses of inesite (Table 3) was made in order to see if a suitable and simple formula could be derived. Two analyses have been excluded[4] from this compilation as they were made on impure material.

TABLE 3. COMPILATION OF CHEMICAL ANALYSES OF INESITE FROM VARIOUS LOCALITIES

	1*	2*	3*	4	5	6**	7**
SiO_2	43.92	43.92	43.67	44.89	42.92	44.50	45.67
MnO	37.87	38.23	37.04	36.53	36.31	37.80	35.10
FeO	0.69	0.69	1.11	2.48	—	0.55[a]	0.92
MgO	0.33	0.28	0.15	trace	0.37	0.27	0.86
CaO	8.40	8.00	9.38	8.24	8.68	7.86	9.33
H_2O-	4.54	8.49	7.17	3.88	10.48	3.66	2.13
H_2O+	4.68			4.32		4.90	6.53
Al_2O_3	0.29	0.29	—	—	—	0.43	none
PbO	—	—	0.77	—	0.73	—	none
	100.72	99.90	99.29	100.34	99.49	99.97	100.54
G.	3.03	3.103	3.03	2.965			

* The single asterisks indicate analyses for which partial optical data are given. (See Table 2, Columns 1, 2, and 3.)

** The double asterisks indicate analyses for which more complete optical data are given (See Table 2, Columns 7 and 13.)

[a] Fe_2O_3.

1. Nanzenbach, northeast of Dillenburg, Germany. Bärwald, analyst.
2. Dillenburg, Germany. Hampe, analyst.
3. Harstig mine, Pajsberg, near Persberg, Vermland, Sweden. Flink, analyst.
4. Villa Corona, Durango, Mexico. Farrington, analyst.
5. Jakobsberg, Nordmark, Långban, Sweden. Lundell, analyst.
6. Anjo mine, Idzu, Japan. Tanaka, analyst.
7. Quinault, Washington. Fairchild, analyst.

These seven analyses of inesite, made by seven different analysts over a period of 50 years, on material from six different localities from five countries show a remarkable uniformity in composition, the variations in the percentages being notably small. The SiO_2 content varies from 42.92% to 45.67%, with a difference of 2.75%; MnO from 35.10% to 38.23%, with a difference of 3.13%; CaO from 7.86% to 9.38%, with a difference of only 1.52%; and H_2O from 7.17% to 10.48%, with a difference of 3.31%. Even the minor constituents are consistently small, FeO reaching a maximum of 2.48 per cent and MgO a maximum of 0.86 per cent.

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[4] Analysis of agnolite, a mineral later shown to be identical with inesite, Breussig, E., *Neues Jahrb. Min., Beil. Band*, vol. **13**, p. 265, 1900, and one of inesite, Goldschmidt, V. M., *Videnskaps. Shrifter*, No. **1**, p. 392, 1911.

Recalculating the analyses to a common basis of 100.00 per cent by discarding Al_2O_3 and PbO, which never reach one per cent in any analysis, and combining the small quantities of FeO and MgO (only two determinations exceed one per cent) on an equivalent basis with MnO, the results obtained are shown in Table 4.

TABLE 4.—RECALCULATED ANALYSES OF INESITE

No.	1	2	3	4	5	6	7	
	Germany, Bärwald	Germany, Hampe	Sweden, Flink	Mexico, Farrington	Sweden, Lundell	Japan, Tanaka	Washington, Fairchild	Average
SiO_2	43.63	44.00	44.18	44.75	43.24	44.65	45.14	44.21
MnO	38.87	39.48	39.07	38.86	37.46	38.88	37.08	38.54
CaO	8.34	8.01	9.50	8.21	8.74	7.88	9.22	8.56
H_2O	9.16	8.51	7.25	8.18	10.56	8.59	8.56	8.69
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

The percentages given in Table 4 are plotted in Fig. 2 in the order of increasing percentages of CaO and hence in the order of analyses Nos. 6, 2, 4, 1, 5, 7, 3, to show diagrammatically the constancy in composition of the several inesites. Not many of the less common minerals show seven analyses on samples from different localities with such a uniformity of chemical composition. The very slight variability in percentages of CaO (shaded in Fig. 2) may be due in part at least to contamination by calcite as every specimen of inesite examined contained calcite, and even hand picked and purified samples show a slight effervescence in acid although none of the analyses report any CO_2.

It is obvious that MnO and CaO do not vary reciprocally in inesite. The percentages of CaO are fully as constant as are those of SiO_2 and of MnO.

Compare, for example, the extent of the variation in the percentages of CaO in inesite, from 7.88 to 9.50 (in the recalculated analyses), with the variations in several sets of analyses of rhodonite, in which CaO and MnO vary reciprocally. Thus, in a compilation of 14 analyses of rhodonite with which optical determinations can be correlated,[5] the percent-

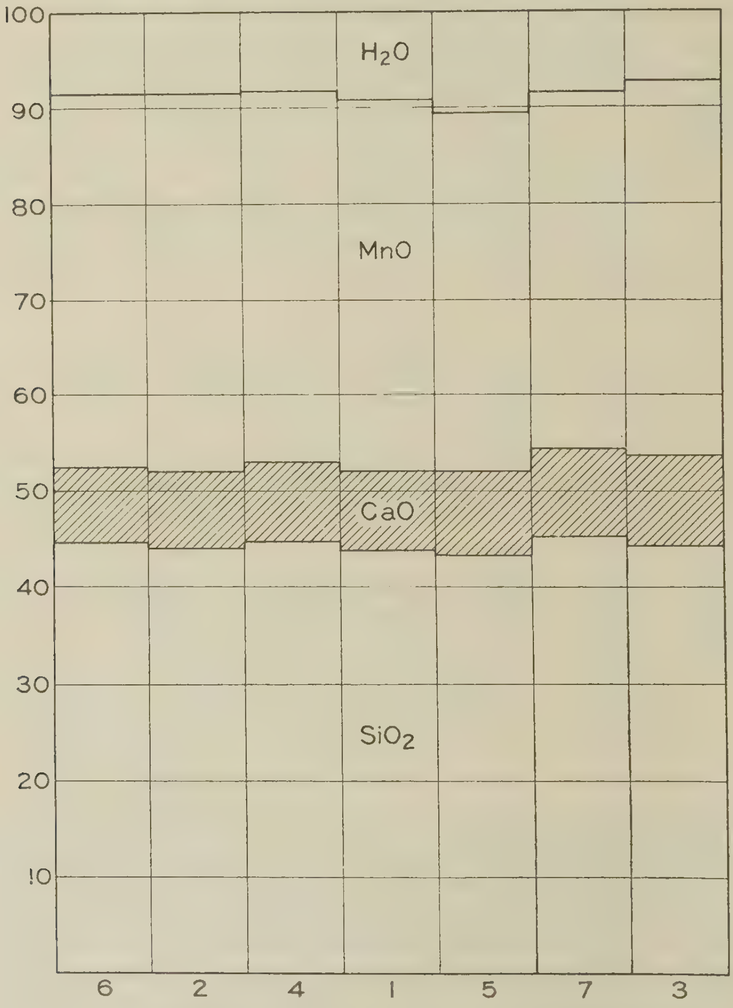

FIG. 2. Diagrammatic representation of the analyses of seven inesites, to show constancy of composition.

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[5] Compilation made by W. T. Schaller.

ages of CaO range from 1.31 to 10.12; in seven analyses from Australia,[6] from 3.50 to 11.08; in seven analyses from New Jersey, listed by Palache[7] from 4.50 to 10.50; and in six analyses from Japan,[8] from 1.48 to 6.96.

The molecular ratios of the different constituents obtained from the recalculated analyses of Table 4 are given in Table 5 on the basis of $SiO_2 = 100$.

TABLE 5. MOLECULAR RATIOS OF ANALYSES OF INESITE, WITH $SiO_2=100$

	1	2	3	4	5	6	7	Av.
SiO_2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
MnO	75.5	76.1	75.0	73.5	73.4	73.8	69.4	73.9
CaO	20.5	19.5	23.0	19.7	21.7	18.9	21.9	20.8
H_2O	70.0	64.6	54.8	61.0	81.5	64.2	63.3	65.7
MnO+CaO	96.0	95.6	98.0	93.2	95.1	92.7	91.3	94.7
$MnO+CaO+H_2O$	166.0	160.2	152.8	154.2	176.6	156.9	154.6	160.4
$\frac{SiO_2}{MnO+CaO}$	1.042	1.047	1.021	1.074	1.052	1.079	1.095	1.056
$\frac{SiO_2}{MnO+CaO+H_2O}$	.602	.624	.655	.649	.566	.637	.647	.623
$\frac{MnO}{CaO}$	3.68	3.90	3.26	3.73	3.38	3.90	3.17	3.55

The molecular ratios shown in Table 5 bring out clearly a number of relationships between the constituents of inesite.

First, there is no simple ratio between SiO_2, MnO, CaO, and H_2O.

Second, the ratio of SiO_2 to MnO+CaO is never 1:1. The proportion of MnO+CaO is consistently less than 100, ranging from 91.3 to 98.0. Hence the ratio of SiO_2 to MnO+CaO is consistently slightly greater than 1.

Third, the ratio of SiO_2 to $MnO+CaO+H_2O$ averages 0.623, or very close to 0.625, which gives a ratio of SiO_2 to $MnO+CaO+H_2O$ of 5:8. Hence, the generalized formula of inesite may be written $5SiO_2 \cdot 8(MnO, CaO, H_2O)$.

Fourth, the ratio of SiO_2 to CaO is rather consistently close to 5:1. The formula may then be written $5SiO_2 \cdot 1CaO \cdot 7(MnO,H_2O)$.

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[6] Stillwell, F. L., The rocks in the immediate neighborhood of the Broken Hill Lode—their bearing on its origin: *Mem. Geol. Survey New South Wales, Geology*, No. **8**, Appendix II, p. 385, 1922.

[7] Palache, Charles, The minerals from Franklin and Sterling Hill, Sussex County, N. J.: *U. S. Geol. Survey, Prof. Paper* **180**, p. 67, 1935.

[8] Harada, Zyunpei, Chemische Analysenresultate von japanischen mineralien: *Jour. Faculty Science, Hokkaido Imperial University, Ser. IV*, vol. **3**, nos. 3–4, p. 279, 1936.

Fifth, the ratio of MnO:CaO is not 4:1, as generally stated, but averages about $3\frac{1}{2}:1$ with considerable variation, from 3.17 to 3.90:1.

Sixth, the ratio of MnO:H_2O is only approximately 1:1, with the MnO in slight excess.

From these relationships, particularly the third and fourth, the molecular ratios of the various constituents may then be restated by changing SiO_2 to 5.00 with the following results (Table 6). In this table, CaO is placed before MnO, immediately following SiO_2, to emphasize the 5:1 ratio between SiO_2 and CaO.

TABLE 6. MOLECULAR RATIOS OF ANALYSES OF INESITE, WITH $SiO_2 = 5.00$

	1	2	3	4	5	6	7	Av.
SiO_2	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
CaO	1.02	.97	1.15	.98	1.08	.94	1.09	1.04
MnO	3.78	3.80	3.75	3.67	3.67	3.69	3.47	3.70
H_2O	3.50	3.23	2.74	3.05	4.08	3.21	3.17	3.28
$MnO+H_2O$	7.28	7.03	6.49	6.72	7.75	6.90	6.64	6.98

A consideration of the ratios given in Table 6 shows a rather close agreement with a 5:1 ratio of SiO_2 to CaO and a 5:7 ratio of SiO_2:($MnO+H_2O$). The slight variation from unity (both plus and minus) in the ratios of CaO are not balanced by corresponding variations in MnO. There is no reciprocal relation between CaO and MnO and the slight variations from unity for CaO are to be explained by errors in analysis and traces of calcite rather than by a real variation in the CaO content.

The ratio of SiO_2 to MnO never reaches 5:4 but varies slightly from 5:3.47 to 3.80, averaging closely to $5:3\frac{2}{3}$. The formula of inesite can then be written $5SiO_2 \cdot CaO \cdot 3\frac{2}{3}\,MnO \cdot 3\frac{1}{3}H_2O$ or $15SiO_2 \cdot 3CaO \cdot 11MnO$. $10\,H_2O$. A comparison between the average recalculated analysis (from Table 4) and the theoretical composition calculated from the above formula shows a close agreement, as shown in Table 7.

TABLE 7. COMPARISON OF AVERAGE RECALCULATED ANALYSIS WITH THE THEORETICAL COMPOSITION CALCULATED FROM THE FORMULA $15SiO_2 \cdot 3CaO \cdot 11MnO \cdot 10H_2O$

	Average Analysis	$15SiO_2 \cdot 3CaO \cdot 11MnO \cdot 10H_2O$	Difference
SiO_2	44.21	44.42	−0.21
MnO	38.54	38.42	+0.12
CaO	8.56	8.29	+0.27
H_2O	8.69	8.87	−0.18
	100.00	100.00	

The differences between the calculated percentages and the seven recalculated analyses (Table 4) are as follows (Table 8).

TABLE 8. DIFFERENCES BETWEEN THE SEVEN ANALYSES OF INESITE AND THE CALCULATED VALUES FOR THE FORMULA $15SiO_2 \cdot 3CaO \cdot 11MnO \cdot 10H_2O$

	1	2	3	4	5	6	7
SiO_2	−0.79	−0.42	−0.24	+0.33	−1.18	+0.23	+0.72
CaO	+0.05	−0.28	+1.21	−0.08	+0.45	−0.41	+0.93
MnO	+0.45	+1.06	+0.65	+0.44	−0.96	+0.46	−1.34
H_2O	+0.29	−0.36	−1.62	−0.69	+1.69	−0.28	−0.31

There is no consistent large discrepancy for any one constituent or for any one analysis. There are 14 negative differences and 14 positive differences. The discrepancies therefore are compensating and for the average analysis very small (Table 7).

It has not been possible to find a simple formula for inesite which agrees closely with the ratios derived from the seven analyses. If, however, in the average ratios (last column, Table 6), 0.28 H_2O be added to the 3.70 MnO, bringing it up to 3.98 or practically 4, the ratio of the remaining H_2O is 3.00, and the simple formula $5SiO_2 \cdot CaO \cdot 4MnO \cdot 3H_2O$ results. This formula requires 40.85 per cent of MnO, a value not reached in any analysis of inesite.

If a slight variability in the proportions of MnO and H_2O be assumed, and the general formula written as $5SiO_2 \cdot 1CaO \cdot 3MnO \cdot 3H_2O \cdot 1(Mn,H_2)O$, the following two simple formulas may be considered as representing the two extremes, between which all analyses of inesite would lie:

$$5SiO_2 \cdot 1CaO \cdot 3MnO \cdot 4H_2O$$
$$5SiO_2 \cdot 1CaO \cdot 4MnO \cdot 3H_2O$$

The percentage composition of these two formulas, compared with the average analysis, is shown in Table 9.

However, the general formula $5SiO_2 \cdot 1CaO \cdot 3MnO \cdot 3H_2O \cdot 1(Mn,H_2)O$ lacks complete definiteness and it seems unreasonable to express a formula with two variables (MnO and H_2O) when these same constituents are also given in the formula as constants. Hence the exact but more complex formula $15SiO_2 \cdot 3CaO \cdot 11MnO \cdot 10H_2O$ is to be preferred.

How the water functions in inesite is not known. The meager data as to H_2O- and H_2O+ are too variable and contradictory to be interpretable.[9] The H_2O- in the seven analyses varies from 2.13 to 4.54 per

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[9] In at least one analysis (no. 3), the water was determined by loss on ignition. This method yields a wrong and too low a value, as shown by Farrington.

TABLE 9. COMPARISON OF AVERAGE RECALCULATED ANALYSIS WITH THE THEORETICAL VALUES FOR THE TWO FORMULAS $5SiO_2 \cdot 1CaO \cdot 4MnO \cdot 3H_2O$ AND $5SiO_2 \cdot 1CaO \cdot 3MnO \cdot 4H_2O$

	$5SiO_2 \cdot 1CaO \cdot 4MnO \cdot 3H_2O$	Average	$5SiO_2 \cdot 1CaO \cdot 3MnO \cdot 4H_2O$
SiO_2	43.29	44.21	46.86
CaO	8.08	8.56	8.75
MnO	40.85	38.54	33.17
H_2O	7.78	8.69	11.22
	100.00	100.00	100.00

cent. Farrington considers 5.99 per cent H_2O as water of crystallization as it was taken up again by the mineral on exposure to ordinary air. It seems doubtful though if any of the water given in the analyses of such a well crystallized mineral as inesite should be considered as unessential. Even if future work should yield a different ratio for H_2O from that here given, the complex formula $15SiO_2 \cdot 3CaO \cdot 11MnO \cdot 10H_2O$ cannot be reduced to a much simpler one as the ratio of CaO+MnO never equals that of SiO_2 but in all analyses is slightly lower.

Note. Since this paper was written, an abstract of a paper describing inesite from New Zealand has appeared.[10] The analysis gives 8.04 per cent CaO and 8.77 per cent H_2O, confirming the suggested constancy of the CaO content of inesite and agreeing closely with the calculated values of the complex formula.

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AN ACCURATE METHOD FOR THE DETERMINATION OF THE COMPONENTS OF A HETEROGENEOUS PARTICULATE MINERAL SYSTEM

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In the course of the development of a precise technique for the use of the petrographic microscope in rock analysis, attempts have been made to determine the mineral constituents quantitatively. Such determinations have had their greatest success when applied to thin sections of rock samples. However, there are numerous occasions when analyses have to be made of powdered material or loose crystals, and the investigator cannot have recourse to such sections. An attempt has been made, therefore, to develop a method which would be generally applicable to this type of material.

Limitations of the Thin-Section Technique

The Rosiwal[1] method of determining the quantitative ratio of mineral constituents in mixed rock samples is ideally adapted to thin or what may be considered two-dimensional sections. Although extensive claims have been made for it, the method is not applicable to mixed particulate substances where it is necessary to measure the intercepts of projections. In fact, even with thin sections, doubt has been expressed as to its accuracy by Julien[2] and later by Williams.[3] Julien pointed out the necessity of considering the shape factor in connection with the use of an average diameter in estimating percentage composition of rocks in general, while Williams showed from careful analyses of Westerly, Rhode Island granite that the results obtained by the Rosiwal method were not in agreement with results obtained by several other generally accepted methods. On the other hand, Johannsen and Stephenson[4] claim remarkable correlations between determinations made by the Rosiwal method and results calculated from chemical analysis, and the method of separation by means of heavy solutions. This result might be expected if Johannsen and Stephenson utilized sections for other analyses similar to those used for the Rosiwal determinations. While this fact is not specifically stated, it is implied. In passing, it is well to point out that Rosiwal in a footnote to the thin-section technique of Delesse states ". . . This thin rock section . . . would have a weight of 1300 mg., and . . . provide sufficient material for an ultimate chemical analysis." As might be expected, if thin sections are used for chemical analysis, excellent correlations should be expected between such determinations and those made by the Rosiwal method.

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The assumption that average diameters as determined from an examination of the projections of a particulate array can be utilized for estimating the percentage composition of an aggregate is erroneous.This fact follows from a consideration of the shapes of the particles themselves. *Unless the volume shape factors of the components under observation are exactly the same, only approximate values of the composition of a given mineral can be obtained.* It will be shown later that the volume shape factors of minerals vary widely. For irregularly shaped particles the volume shape factor can be shown to be always less than $\pi/6$ (the value for a sphere). The lack of attention to this fact has undoubtedly led to numerous discrepancies which might have been otherwise explained.

THEORY OF METHOD PROPOSED

Statistical Description of an Aggregate

It is evident from the foregoing that the method of linear intercepts as developed by Rosiwal is applicable only to a two-dimensional distribution. In order to apply such a method to a heterogeneous assembly of particles, the particles must first be imbedded in a suitable medium and sectioned. This process is not only involved and time consuming, but is often impossible to accomplish successfully, especially when the particles are small. However, it is possible to obtain an accurate estimate of the mass of an aggregate without recourse to either the Rosiwal or Delesse methods elsewhere described. This new approach depends upon certain parameters which define the properties of an aggregate. Thus, it is known that the mass of a particle varies as the cube of a dimension:

$$W = \nu\rho d^3 \qquad (1)$$

where W defines the weight of a particle of diameter d and density is ρ. The term ν may be called a shape factor which has a specific value for each particulate aggregate. The value of ν need not be constant for a given mineral and must be determined. Hence, for a sphere ν is equal to 0.5286. For irregularly shaped bodies, it may be shown that ν has a value less than that of a sphere.

Hatch and Choate[5] have pointed out that for a heterogeneous aggregate, an average value of D is obtained by measuring the intercepts of particles along a fixed direction. If the particles are uniformly distributed and all particles along a given fixed direction are measured, then the distribution may be assumed to follow the curve:

$$N=\frac{\Sigma n}{\log \sigma_g \sqrt{2\pi}}\, e^{-(\log d-\log M_g)^2/2 \log^2 \sigma_g}\,. \tag{2}$$

where N is the number of particles of a size d, σ_g is the geometric standard deviation and M_g is the median value of the distribution. Both σ_g and M_g are constants that determine the position and shape of the distribution.† They are given by the algebraic equations

$$\log M_g=\frac{\Sigma(n \log d)}{\Sigma n}$$

and

$$\log \sigma_g=\sqrt{\frac{\Sigma\left[n(\log d-\log M_g)^2\right]}{\Sigma n}}\,.$$

The work entailed in the calculation of M_g and σ_g may be considerably reduced if, following the method proposed by Hatch and his coworkers, a special log-probability grid is used. As a rule, skew frequency data plot as a straight line on this type of grid. The median value M_g may be directly obtained by observing the value for which 50 per cent of the particles are less than the stated size. The value of σ_g may be determined from the grid by calculation of the following ratio:

$$\sigma_g=\frac{84.13 \text{ per cent size}}{50 \text{ per cent size}}=\frac{50 \text{ per cent size}}{15.87 \text{ per cent size}}\,.$$

The above follows from the probability integral.

In the problem on hand we are concerned with a comparison between known weights of an aggregate of particles and a calculated weight based upon the statistical parameters M_g and σ_g. This requires a relation between these parameters and the volumetric properties of the system under consideration. Thus, if D defines the diameter of a particle in the aggregate having an average volume, we have

$$D=\sqrt[3]{\frac{\Sigma(nd^3)}{\Sigma n}}$$

or, from equation 2

$$\frac{\Sigma(nd^3)}{\Sigma n}=\frac{\Sigma n}{\log \sigma_g \sqrt{2\pi}}\int_0^\infty d^3 e^{-(\log d-\log M_g)^2/2 \log^2 \sigma_g}\, d \log d$$

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† The size frequency equation above is for a skew distribution. It assumes, of course, asymptoticity of values at both extremes, a condition which is rarely true with particulate substances, but for practical purposes, as will be shown, is sufficiently accurate.

from which it may be shown

$$\frac{\Sigma(nd^3)}{\Sigma n} = e^{3 \log M_g + 4.5 \log^2 \sigma_g}$$

or reduced to the base 10

$$\log D^3 = \log M_g^3 + 10.3617 \log^2 \sigma_g. \tag{3}$$

Determination of Components

From equation 3, D may be readily calculated. Hence for a two component system α, β, the determination of the statistical parameters M_g and σ_g leads directly to an estimation of the mass of all the particles counted and measured in a given field. (That is, in any field all particles must be counted and measured with due regard to their identity. In a two-component system this implies the identification, count, and measurement of all α particles in a series of fields and all β particles in other fields, assuming, of course, that the fields are representative of the sample under examination.) Thus, we may write

$$\frac{\text{Weight of } \alpha-\text{particles, } W_\alpha}{\text{Weight of } \beta-\text{particles, } W_\beta} = \frac{\nu_\alpha \rho_\alpha N_\alpha D_\alpha^3}{\nu_\beta \rho_\beta N_\beta D_\beta^3} \tag{4}$$

and if ν_α, ν_β, ρ_α, ρ_β are known and N_α, N_β, D_α, and D_β are determined the percentage composition of the two-component system is readily determined

$1/\left(\frac{W_\alpha}{W_\beta}+1\right) \times 100 =$ percentage of β component, and $100 - 100\ W_\beta$ $= 100\ W_\alpha$.

The extension to an n-component system is equally simple, although tedious, since it requires the determination of the shape factor ν and density ρ for all components together less the component under determination. This procedure, however, is not always possible.

Let the components of the n-component system be α_1, α_2, $\alpha_3 \cdots \alpha_n$; we may then write symbolically for determining the α_1 component, assuming all the α-components taken together to be $\Sigma\alpha$.
Hence

$$\frac{\text{Weight of } \alpha_1 \text{ particles, } W_{\alpha_1}}{\text{Weight of } _{\Sigma\alpha} \text{ particles, } W_{\Sigma\alpha}} = \frac{\nu_{\alpha_1} \rho_{\alpha_1} N_{\alpha_1} D_{\alpha_1}^3}{\nu_{\Sigma\alpha} \rho_{\Sigma\alpha} N_{\Sigma\alpha} D_{\Sigma\alpha}^3} \tag{5}$$

Successive applications of this procedure may in certain cases be used to determine several components of a system.

Availability of Data on ν and ρ

Values of the volume shape factor ν for various minerals are generally not available from the literature. Hatch, by the procedure outlined above for determining the statistical parameters M_g and σ_g and D, and by substitution in the equation

$$W = \nu \rho D^3$$

obtained the following values of ν.

For quartz	0.14
For granite	0.14
For calcite	0.135

These values are much less than the value for a sphere ($\pi/6 = 0.5286$). Thus, the assumption that particles are spheres may, as Hatch and Choate point out, leads to considerable errors. In the present investigations, a hypothetical value of unity was assigned as the shape factor of one component (quartz), and from an *a priori* knowledge of the densities of the components and all other factors, the relative shape factors for other components could be determined. Thus, from equation 4, assuming $\nu_\alpha = 1$,

$$\nu_\beta = \frac{W_\beta \rho_\alpha N_\alpha D_\alpha{}^3}{W_\alpha \rho_\beta N_\beta D_\beta{}^3} \cdot$$

This procedure unfortunately does not yield absolute values of ν which are frequently desired as a matter of interest. In a later paper, the authors will show how the shape factor varies with size distribution (D and σ_g) for various minerals.

Values for the density of a given mineral can generally be secured from petrographical handbooks. Where some question exists, however, as to the value of a given mineral or mineral aggregate, pycnometer determinations can be readily made.

Procedure Used in Present Investigation

For the purpose of this investigation, mineral powders were selected of a size range and properties so that microscopic identification was fairly simple. The minerals were all crushed and then sieved. The portion passing through a 200-mesh sieve and retained on a 325-mesh sieve was used as a stock sample. Its specific gravity was determined and it was also given a preliminary petrographic examination. Determinations were then made as follows:

A mixture of two minerals was made up by weighing out a definite quantity of each on the analytical balance so that the total weight of the sample was about one gram. The sample was then thoroughly mixed by shaking it in a small glass weighing bottle.

A slide of the sample was next prepared. A pinch of the material was transferred to the slide by means of a small knife blade. A drop of the immersion media was added and after mixing as well as possible it was covered with a 13 mm. cover glass, taking care that air bubbles had been excluded.

The slide was then examined with the petrographic microscope using a 16 mm. objective (10×). The microscope was also equipped with a filar micrometer. All the particles in a field were identified, measured, and counted. The diameter of the particle read off was its maximum projection on a given straight line which was used as a base line for all measurements. With the aid of a person to take down the readings on the filar micrometer, it took about three hours for the microscopic examination. This is very short, indeed, when we consider the time required for a chemical analysis.

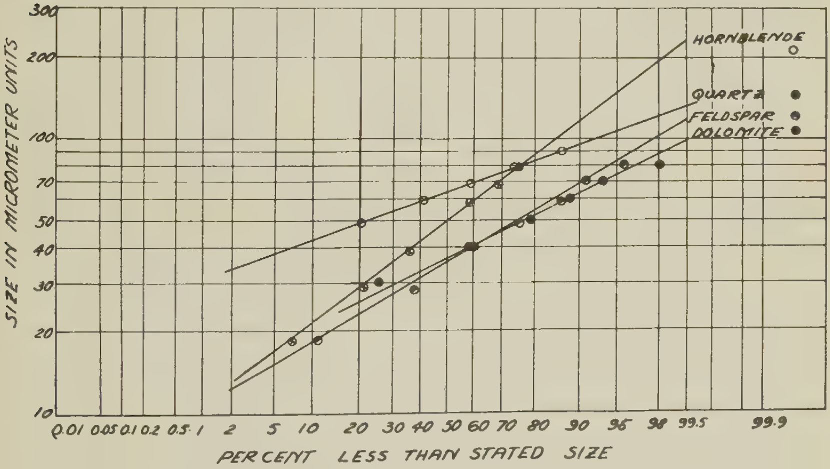

FIG. 1. Size frequency summation curves for determining M_g and σ_g

DATA AND RESULTS

Table 1 gives the necessary data for the four minerals studied in order to determine their percentage composition when mixed with one another. M_g and σ_g are read off from the curve in Fig. 1. The average diameter D is then calculated from equation 3. ν is obtained from equation 4 by starting with a mineral system α_β whose percentage composition and ν_α are known.

TABLE 1.—STATISTICAL CONSTANTS FOR VARIOUS PARTICULATE MINERALS STUDIED

Mineral	Density (ρ)	Geom. med. (M_g)	Geom. S. D. (σ_g)	Average diameter* (D)	Relative volume shape factor ν quartz = 1
Quartz	2.65	63.0	1.4	74.6	1.000
Hornblende	3.22	49.0	1.9	90.9	0.157
Feldspar (orthoclase)	2.57	35.0	1.6	51.0	1.86
Dolomite	2.85	35.0	1.6	47.6	1.36

* In micrometer units. One micrometer unit = 1.1 microns.

It is to be noted that although all of these minerals have been crushed and sieved in the same way, their diameters show large differences. The average diameter of hornblende is 90.9 while for dolomite it is only 47.6. Hornblende gave a standard deviation of 1.9 while for quartz it is 1.4. It may therefore readily be seen how assumptions concerning uniformity of size and shape[6,7] will lead to erroneous results in estimations of volume—or weight—percentages of the components of a particulate system.

TABLE 2.—RESULTS OF DETERMINATIONS OF VARIOUS PARTICULATE SYSTEMS STUDIED

Sample No.	Mineral system α - β	No particles α	No particles β	Value of α determined (Per cent)	Actual value of α (Per cent)	Remarks
H-1	Quartz-Hornblende	375	132	89.0	89.6	
H-2	Quartz-Hornblende	103	100	75.8	73.1	
H-3	Quartz-Hornblende	254	274	72.5	73.1	Check on H-2
H-4	Quartz-Hornblende	255	246	74.6	73.1	Check on H-2
H-5	Quartz-Hornblende	200	228	71.3	73.1	Check on H-2
H-6	Quartz-Hornblende	200	519	52.3	49.5	
H-7	Quartz-Hornblende	100	2651	9.2	10.0	
F-1	Quartz-Feldspar	92	190	56.2	50.3	
F-2	Quartz-Feldspar	193	203	71.6	69.3	
F-3	Quartz-Feldspar	595	200	9.9	10.0	
F-4	Quartz-Feldspar	330	106	9.9	10.0	Check on F-3
D-1	Quartz-Dolomite	50	197	50.6	50.6	
D-2	Quartz-Dolomite	198	211	79.1	79.0	
D-3	Quartz-Dolomite	450	200	90.1	90.1	
D-4	Quartz-Dolomite	65	361	42.1	40.7	
DF-1	Dolomite-Feldspar	217	211	40.4	48.9	
DF-2	Dolomite-Feldspar	362	200	54.4	54.3	
DF-3	Dolomite-Feldspar	368	201	54.7	54.3	Check on DF-2

Table 2 shows the various combinations of minerals which were determined. Each one of these samples was in turn used to calculate the shape factor ν_α so that the value of α determined is based on the average value of ν_α.

A further check on the method is given by the dolomite-feldspar samples since the value of ν is obtained from quartz-dolomite and quartz-feldspar instead of from an additional dolomite-feldspar sample.

It is necessary to count enough particles of a component so that its size distribution curve (Fig. 1) does not change. Two hundred particles are usually sufficient. Once this curve has been determined for each component of a given system, it is only necessary to count enough particles so that the ratio of N_α to N_β is constant. For example, in sample D-1, only fifty quartz particles and 197 dolomite particles were counted.

SUMMARY

The results obtained in this study show, first, how the shape factor for a mineral may be obtained; second, how the size distribution curve can be plotted; and finally, how with this data the percentage by weight of any constituent may be determined by making a count of the number of particles present. The method is applicable to all powders and rock dusts provided that they have a uniform distribution and that they are large enough to be counted and identified.

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TEEPLEITE, A NEW MINERAL FROM BORAX LAKE, CALIFORNIA

W. A. Gale, *American Potash & Chemical Corporation, Trona, California;* William F. Foshag,[1] *U. S. National Museum;* and M. Vonsen, *Petaluma, California.*

Borax Lake, in Lake County, California, was the earliest commercial source of borax in the United States. This mineral was first found there by Doctor John A. Veatch in 1857, and for ten years the lake was actively exploited. The mineral occurs as crystals of borax, oftimes of large size, in a saponaceous mud. A narrow ridge separates Borax Lake from the fresh waters of Clear Lake. Immediately beyond the ridge lies Sulfur Banks, a solfatara which yields highly boraciferous waters. Near the shores of Borax Lake is a small extinct solfatara, known as Little Sulfur Banks, and is probably the original source of the borax. Analysis of water[2] from Borax Lake showed a high content of sodium carbonate, sodium chloride and sodium borate, but with low sodium bicarbonate content.

During the late summer of 1934, Borax Lake became almost completely dry, due to a prolonged period of unusual dry weather and the lake was reduced to a mud playa, covered by a white efflorescence of salts, a condition not observed since 1861, when the lake was reported to have completely dried. In the pools of brine remaining, crusts of salts were formed, and in the central area, covering as much as an acre or two, a shallow pool remained, beneath which beds of saline minerals of a light buff color were deposited.

Analysis of Borax Lake Brine

F. H. May, *Analyst*

Na_2CO_3	14.69
$Na_2B_4O_7$	0.87
$Na_2B_2O_4$	4.32
KBr	0.03
KCl	3.40
NaCl	10.60
Na_2SO_4	0.323
S^{--}	tr.
As_2O_3	tr.
P_2O_5	0.133
I	None found
Organic matter	Appreciable
H_2O, etc. (by difference)	65.64
pH	11.1
Sp. Gr. (20°C.)	1.332

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[1] Published with the permission of the Secretary of the Smithsonian Institution.

[2] Geology of the quicksilver deposits of the Pacific slope: *Mon.* **13,** *U. S. Geol. Surv.*, p. 265, 1888.

In this central portion of the lake bed, immersed and covered by a thick brown viscous brine, were bodies of salts, the largest about sixty feet in length. The viscous liquid upon analysis showed the above composition on the basis of hypothetical combinations in which the components of the reciprocal salt pair $Na_2CO_3-Na_2B_4O_7$ and $NaHCO_3-Na_2B_2O_4$ are expressed in terms of the three salts shown.

Recalculating the main constituents on the basis of grams per 100 grams of water, the results shown in column A below were obtained:

Main Constituents of Borax Lake Brines

	Grams/100 grams H_2O	
	A	B
Na_2CO_3	22.38	22.4
$Na_2B_2O_4$	6.58	6.7
$Na_2B_4O_7$	1.32	0.3
NaCl+KCl	21.33	23.1

In column B is given the composition of the liquid phase at the end point of crystallization in the system $NaCl-Na_2CO_3-NaHCO_3-Na_2B_4O_7-Na_2B_2O_4-H_2O$ at 35°C., at which halite, trona, $Na_2B_2O_4\cdot 2NaCl\cdot 4H_2O$ and $Na_2CO_3\cdot H_2O$ are in equilibrium with the solution.[3] It is evident from these compositions that the compound $Na_2B_2O_4\cdot 2NaCl\cdot 4H_2O$ and $Na_2CO_3\cdot H_2O$ (or $Na_2CO_3.7H_2O$, which is in equilibrium with this solution at a somewhat lower temperature) would be expected to be present in the salts found in this central portion of the lake.

A number of specimens of these salts, which when first collected, were thought to be trona pseudomorphous after halite, proved upon further examination to be $Na_2B_2O_4\cdot 2NaCl\cdot 4H_2O$, which had formed upon and largely replaced halite. Since this compound is new in nature, although well known as an artificial compound, having been first prepared by W. E. Burke at the Searles Lake plant in 1920, it is here proposed to give it the mineralogical name, *teepleite*, for the late Dr. John E. Teeple, in recognition of his contribution to the chemistry of Searles Lake salts.

The salts that formed during the desiccation of the lake consist of buff colored crusts of crystals made up of cubes of halite, blades of trona and crusts of teepleite. Borax is absent in these specimens. The specimens show strong indications that in many cases cubes of halite have reacted with the mother liquor to form teepleite as the composition of the brines changed through crystallization, giving rise to pseudomorphs of teepleite after halite. The sequence of crystallization was (1) halite, (2) trona, (3) teepleite, and (4) $Na_2CO_3\cdot 7H_2O$ (?).

[3] Teeple, John E.: The Industrial Development of Searles Lake Brines, with Equilibrium Data, **1929**, p. 130.

Later in the season, after several rains and cooler weather, teepleite disappeared and halite again crystallized in fresh, glassy cubes.

CHEMICAL PROPERTIES

Material for analysis was selected from the groups of teepleite crystals grown upon halite and trona. Their surfaces were scraped to remove adhering salts but the sample contained inclosed blades of trona. Attempts to separate the teepleite from the trona by heavy solutions discolored the teepleite, due to reaction with the organic heavy liquids, so that the best possible sample was prepared by hand picking. Microscopic examination showed the prepared sample carried trona and a little halite, but no other contaminant. The results of the analysis is given in the table below:

ANALYSIS OF TEEPLEITE, BORAX LAKE, CALIFORNIA

William F. Foshag, *Analyst*

	Percentages	Ratios	Theory for $Na_2B_2O_4 \cdot 2NaCl \cdot 4H_2O$
Na	28.93	1.2565	28.70
K	None	—	
Ca	0.08	.0021	
Cl	18.72	.5279	22.15
B_2O_4	22.05	.2574	26.70
CO_3	9.42	.1519	
SO_4	None	—	
H_2O	20.48	1.1366	22.45
Insol.	0.15		
	99.83		100.00

After deducting the calcium as $CaCO_3$ and the remaining CO_3 as trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2\frac{1}{2}H_2O$), the remaining ratios, attributable to teepleite ($Na_2B_2O_4 \cdot 2NaCl \cdot 4H_2O$) are as follows:

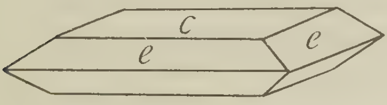
	Ratios	
Na	1.0318	4×2579
B_2O_4	.2574	1×2574
Cl	.5279	2×2639
H_2O	.9494	4×2376

These ratios except for the low water value, which may be explained, in part at least, by the dehydrated appearance of some of the teepleite, indicate satisfactorily the composition $Na_4B_2Cl_2O_4 \cdot 4H_2O$ or, written as a double salt, $Na_2B_2O_4 \cdot 2NaCl \cdot 4H_2O$.

Teepleite is easily soluble in water to an alkaline solution and gives the usual reactions for chloride and borates. Before the blowpipe, or on a platinum wire, it fuses easily to a white enamel-like crystalline bead, coloring the flame strongly yellow with a momentary flash of green.

CRYSTALLOGRAPHY

Teepleite occurs in crystals but measurable individuals on the material collected are rare. The crystals are flat, beveled plates, usually rounded into flat cushion shape or even lens-shaped individuals. The crystals are usually aggregated into small nubbins, giving a botryoidal effect. Sometimes they are grouped into "roses." Two natural crystals suitable for measurement were found, the measurements of which yielded the data upon which the crystallographic properties were determined. A number of artificial crystals were prepared but did not yield any more satisfactory data.



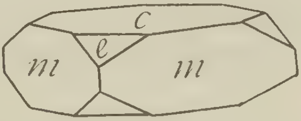


FIG. 1. Teepleite, Borax Lake, Lake County, California.
FIG. 2. Artificial teepleite.

Teepleite is tetragonal, of simple crystal habit. Only the base $c\{001\}$ and the pyramid $e\{101\}$ were found. The base is large, the pyramids relatively narrow, so that the crystals are flat, tabular to the base (Fig. 1). The artificial crystals showed, in addition to the two above forms faces of $m\{110\}$, (Fig. 2).

On crystal No. 1, three good readings for the face $e\{101\}$ gave $\rho = 33°49'$, while 3 fair readings on crystal No. 2 gave $\rho = 33°43'$, $33°40'$ and $33°42'$. The weighted average for ρ for $e(101) = 33°47'$. From this the axial ratio was calculated $a:c = 1:0.6690$. Seven measurements for e, on artificial crystals, gave $\rho = 33°42'$ (average), the individual values ranging from $33°39'$ to $33°54'$.

To Mr. George Switzer we are indebted for the determination of x-ray measurements on teepleite. The unit cell dimensions of the simple tetragonal lattice are: $a = 7.27$ Å; $c = 4.84$ Å, with $c = 0.666$, which agrees well with the morphological ratio: $c = 0.6690$. Since the morphology indicates the holohedral crystal class $4/m2/m2/m$, the space group $P4/nmm$ (D_{4h}^{7}) is fixed by the following observed reflections: $h\ k\ l$ all orders present, $h\ k\ 0$ present only when $h+k$ is even, $0\ k\ l$ all orders present and $h\ h\ l$ all orders present. These observations and measurements were made upon artificial crystals since the natural crystals available were not suitable.

PHYSICAL AND OPTICAL PROPERTIES

The color of the natural teepleite is white to pale buff. This latter color is induced in the mineral by the organic matter in the brines, which in the final state of desiccation of Borax Lake colored the waters molasses brown. Artificial crystals are clear and transparent to white. The luster of the natural mineral is glassy to somewhat greasy, becoming duller upon exposure. The mineral is uniaxial, negative. Indices of refraction on both the natural and the artificial crystals are:

	Natural	Artificial
$\epsilon=$	1.503	1.503
$\omega=$	1.519	1.521

The mineral has a hardness of 3–3.5 and is very brittle. Its fracture is irregular to semi-conchoidal. The specific gravity, determined upon a selected fresh fragment by floating in heavy solution, is 2.076.

SUMMARY

Teepleite is a sodium borate chloride, $Na_2B_2O_4 \cdot 2NaCl \cdot 4H_2O$. Tetragonal. $c=0.6690$. Uniaxial, negative. $\epsilon=1.503$, $\omega=1.519$. H=3–3.5. G.=2.076. Occurs with halite and trona on specimens from Borax Lake, Lake County, California.

PRESENTATION OF THE SECOND ROEBLING MEDAL OF THE MINERALOGICAL SOCIETY OF AMERICA TO WALDEMAR T. SCHALLER

A. Presentation—Esper S. Larsen, *Harvard University, Cambridge, Mass.*

Over a period of years the Mineralogical Society of America accumulated from its income a fund "to establish awards, either medals or money prizes, to be given to outstanding investigators in America or abroad, or to the authors of contributions adjudged as noteworthy. To be the recipient of a medal or prize of the Mineralogical Society of America would soon be recognized as a signal honor, one that would be greatly coveted." The medal has been named the Roebling Medal in memory of Colonel Washington A. Roebling, who so generously supported and endowed the Society.

The second award of the Roebling Medal has been made to Doctor Waldemar T. Schaller in recognition of his outstanding contributions to chemical mineralogy, to crystallography, to the paragenesis of the pegmatite minerals, and to systematic and descriptive mineralogy.

Waldemar T. Schaller was born in Oakland, California, in 1882. He received his preparatory education in the Public Schools of Oakland and San Francisco and studied at the University of California under Professors Eakle and Lawson, and received the degree of Doctor of Philosophy at Munich in 1912. In 1903 he joined the Division of Chemical and Physical Research of the United States Geological Survey and has served as chemist and geologist of that organization to the present time. He is a charter member of the Mineralogical Society of America, served as vice-president in 1921, as president in 1926, and as treasurer since 1931. He is a member of the American Association for the Advancement of Science, the American Chemical Society, Geological Society of America, American Institute of Mining and Metallurgical Engineers (Chairman, Washington section, 1937), American Academy of Arts and Sciences, Washington Academy of Sciences (vice-president 1936–37), Geological Society of Washington (vice-president 1934, president 1935), Mineralogical Society of Great Britain and Ireland, Deutsche Mineralogische Gesellschaft, Société Française de Minéralogie, Wiener Mineralogische Gesellschaft, and is one of the four honorary members of the New York Mineralogical Club.

Doctor Schaller has published 148 papers and reports. The extent of his researches in mineralogy is shown by the facts that in the Second Appendix of Dana's "System of Mineralogy" his work was cited on 29

WALDEMAR T. SCHALLER, *recipient of the Roebling Medal of the Mineralogical Society of America.*

pages with 34 references, and in the Third Appendix on 60 out of 87 pages and with 114 references.

His conclusion, published in 1916, that water or hydroxyl is a necessary constituent of tremolite has since been verified, and it has led to our present interpretation of the composition and structure of all the amphiboles.

In his bulletin of 174 pages on the mercury minerals of Terlingua, Texas, he described in detail and critically discussed many new forms for these minerals, including 102 new forms on terlinguaite. He has described and named 41 new minerals.

Some of his more important contributions are: his description of crystals of turquois and the determination of the composition of turquois; his study of the calcium antimonates, schneebergite, romeite, and atopite; his discussion of the composition of the melilite group; his work on the alunite-jarosite group, including argentojarosite, the only mineral of silver that contains oxygen; his researches on the vanadium minerals in which he determined eight new minerals; that on the borate minerals in which he described four new minerals; and his discussion of the saline minerals of the New Mexico-Texas potash field. His study of the crystal cavities of the New Jersey zeolite region finally determined the origin of these striking phenomena. He served as a member of the War Industries Board on mica and compiled many reports on mineral resources. His 66-page report on mica has been used as a standard by subsequent writer on mica.

Early in his career Doctor Schaller began his investigation of the pegmatites of Southern California, and he has since studied many other pegmatites. From his extensive researches he has shown that many pegmatites are not simple igneous injections but have been formed in part by a long and complicated succession of mineral replacements.

As Chairman of the Committee on Nomenclature of this Society he was largely responsible for securing coöperation with a similar committee of the British Mineralogical Society and for achieving uniformity in mineralogical nomenclature.

As mineralogist of the Federal Survey, his frank and friendly helpfulness and criticism have done much to insure a high quality for the mineralogical work of that Survey. I can personally express my appreciation for much help, inspiration and encouragement from him over a long period of years during which I was privileged to enjoy and profit by his frank criticism, generous helpfulness and loyal friendship.

Doctor Waldemar T. Schaller, on behalf of the Mineralogical Society of America, I present to you the Roebling Medal, awarded to you in recognition of your outstanding investigations in the science of mineralogy.

B. RESPONSE—WALDEMAR T. SCHALLER

Whatever success one may achieve through the years in his chosen profession, nothing gives him greater pride than recognition from his colleagues and fellow workers. So when you, my colleagues and friends, through the Mineralogical Society of America, bestow on me the high award of the Roebling Medal, my heart fills with pride and happiness in the thought that you have recognized my work and have deemed me worthy of the award.

That it is the Roebling Medal gives me added pleasure for I, too, enjoyed the warm friendship of Colonel Washington Augustus Roebling and spent many pleasant hours and even days in his company. Ever ready to contribute time, knowledge, and material for the advancement of mineralogy, his collection has been, and still is, of inestimable value. The Roebling endowment has enabled *The American Mineralogist* to forge ahead and become one of the leading scientific journals of the world. That in this forging ahead I have had a part for eight years as your Treasurer and custodian of the Roebling endowment, has also been a source of satisfaction, for I view it as a partial return to Colonel Roebling for the many favors he extended to me. I have a feeling, too, that, though his gift was unconditional, I am helping to carry out his implied wish by using the income from the endowment solely for the betterment of *The American Mineralogist.*

Colonel Roebling, with a practical knowledge of minerals that few of us have, was extremely modest. When I wrote him some years back that he had been nominated for the Vice-Presidency, he replied: "I am delighted to gather from yours of the 23d that I am not eligible to a higher position in the Mineralogical Society. I am not a mineralogist in the proper sense of the word—in fact, I am only a collector with a smattering of knowledge."

How proud he was of his fine collection and what delight he took in showing a specimen of some rare mineral to one who had never seen that mineral. When the first edition of Larsen's Tables appeared he wrote me: "On page 33 Larsen gives the names of 28 minerals which he has not been able to find—I have 24 of them." Such brief, pertinent, sometimes pungent phrases, seldom more than three or four words in length, were characteristically appended to many of his sentences. If I may quote a few others taken from some of his letters:

"A man brought me a yellow transparent topaz crystal, 13 inches long and 1 inch wide, for which he wanted $2,500. He has it yet."

"For a miserable lehnerite a dealer asks $75—worth $5."

Mentioning a certain collection, he writes: "There are hundreds of specimens of iridescent pyrite, all exactly alike—that is no fun."

"It has been my experience that only very busy men find time to do anything. The others, never."

"Had a visit from Mr. Vaux of Philadelphia. He wonders why I collect specimens. So do I."

Sometimes he would express his adverse opinion of the action of others in a pithy and subtle way. Referring to a distant relative who had inherited a farm, the Colonel wrote me:

"Having inherited a large farm he was obliged to drop minerals for cows."

Again, so-and-so

"Sends me a pen and ink sketch of the Paterson quarry. It took him nearly a year. A work of infinite labor and patience, on which only a German could waste his time."

As a boy I found my greatest pleasure in roaming over the hills around San Francisco Bay, collecting minerals and rocks, making many trips to Tiburon Peninsula hunting for lawsonite, reading avidly the reports of the California State Mineralogist—I still remember the hesitancy of Henry S. Durden in first giving copies of these State reports to such a youngster—gloating over the bulletins of the U. S. Geological Survey, by Lindgren and Melville, on California minerals. How anxiously I awaited the arrival of the postman bringing me those precious volumes from Washington!

It soon became my one desire to become a member of the Division of Chemical and Physical Research in the U. S. Geological Survey. This was the position I craved above all others—to be working on minerals and to be associated with Lindgren, Clarke, Hillebrand, and the other Survey men. For 35 years now, the better part of one's working life, this craving has been fulfilled.

Through the generosity of Albert F. Holden, I was enabled to spend 1912 in Europe and at Heidelberg I too, sat in a "dark little room" with Victor Goldschmidt.

Charles Palache preceded me in Berkeley by a dozen years. While I cannot say, as he did a year ago, that Professor Lawson saved me from a mining career which I likewise "hated in anticipation,"—I was in the mining college for three years—yet Lawson's warm interest in any sincere student of geology and his remarkable ability as a teacher, both in the laboratory and in the field, had a great influence on me to follow geology as a career.

Professor Arthur S. Eakle came to Berkeley to teach mineralogy when

I was half way through college. His influence soon fanned the fire kindled by others to an all consuming desire to follow mineralogy the rest of my days. One day a distinguished visitor, with a pointed beard, returned to old South Hall in Berkeley and happening to meet me in the hallway asked where he could find Professor Eakle. When I afterwards asked Professor Eakle who this gentleman was he replied: "Why that was the great Palache from Harvard." Later, Eakle was making arrangements with Palache for me to be his assistant at Harvard, when I received the appointment in Washington. What a great crystallographer I might have become had I gone to Harvard and studied under Palache!

The University of California may be proud of the fact that, within a year, plus a few days, national societies will have conferred medals on three Berkeleyites. It must also be a matter of great pride to Professor Lawson, who is receiving the Penrose Medal on Friday, that the other two recipients are former students of his.

What a great satisfaction it is to live one's life doing the things one loves to do—in my case, working out new minerals, testing the validity of new species described by other investigators, determining the change in properties with varying chemical composition, and, with it all, giving to minerals their geochemical and geological background. In other words, trying to find out what were the processes of nature that yielded the minerals we now preserve in our collections.

What a satisfaction also to have contributed perhaps a mite to our store of knowledge, to have helped others and to have enjoyed their warm friendship, engendered by a community of interest, and now, to have one's associates say that you have done well and for them to express this thought with this tangible award, "For meritorious achievement."

For the great honor you have bestowed on me, I most sincerely thank you.

NOTES AND NEWS

THE SOPER, OKLAHOMA METEORITE[1]

F. C. Wood[2] and C. A. Merritt[3]

On March 14, 1938, Mr. T. J. Stockton of Soper, Oklahoma, forwarded a specimen to the Oklahoma Geological Survey with the request that it be identified. He had picked up this peculiar material while working on a farm about six miles northwest of Hugo, Oklahoma. The exact location of the find was NE¼ sec. 4, T. 6 S., R. 16 E., Choctaw County, Oklahoma.

This specimen proved to be a meteorite and it has been given the locality name: Soper, Oklahoma meteorite, by the authors.

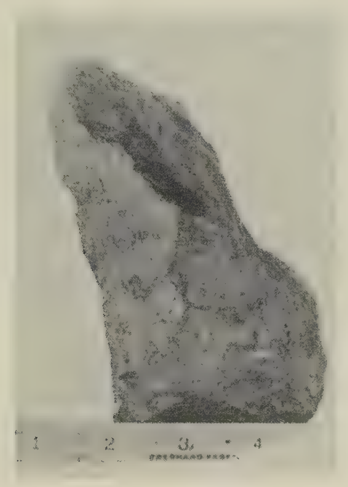


Fig. 1. Illustrating the general shape of the meteorite.

The meteorite is irregular in shape though somewhat pointed at one end, figure 1. A noticeable feature is the sharp ridges formed by the intersections of the various surfaces with one another. Its maximum dimensions, as found, were: length, 6½ inches; width, 5½ inches; thickness, 3 inches. The original weight was 3700 grams. The specimen is pitted with shallow to deep oval-shaped depressions, which approximate a man's thumb in size.

To date no additional fragments of meteorites have been found in this vicinity and there is no evidence as to whether or not this material was a portion of a larger meteorite.

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[1] Published with the permission of the Director of the Oklahoma Geological Survey.

[2] Oklahoma Geological Survey.

[3] University of Oklahoma, and associate member, Oklahoma Geological Survey.

The specimen has been slightly weathered and a thin crust of oxidized material, one millimeter thick, coats the outside. This altered surface has a dull luster and is dark gray to black in color, with a few spots of reddish or yellowish material. The unweathered inner portion of the meteorite is bright, shiny and steel-gray in color. A freshly polished surface developed a few small reddish spots of oxidized material after exposure to the atmosphere for a period of one month. The slight amount of weathering of the specimen as found, probably indicates that the fall was rather recent.

A chemical analysis of the bright unoxidized material gave the following results:*

Insoluble residue**	0.07%
Fe	90.89%
Ni	6.21%
P	2.23%
Co	0.70%
C	0.02%
S	0.03%
Al	0.10%
Cl	trace
Cu	—
Ti	—
Mn	—
Total	100.25%
Specific Gravity	7.387

* Analysis by S. G. English, Chemist of the Oklahoma Geological Survey.

** Insoluble residue—after treatment with concentrated HCl, H_2SO_4, and HNO_3 acids.

The iron, nickel and cobalt contents of this specimen are quite similar to those of many of the iron-nickel meteorites reported in the literature. The percentages of carbon and sulfur likewise are typical. The amount of phosphorus, 2.23%, however, is exceptionally high. In the analyses of the iron-nickel meteorites listed by Merrill,[4] the phosphorus ranges between 0.03 and 0.365%. This element is present in meteorites as a constituent of schreibersite. This mineral has the theoretical formula $(Fe, Ni, Co)_3P$, but admittedly its chemical character varies considerably in different specimens. The meteorite described in this paper appears to be unusually high in this phosphide mineral.

A polished specimen of the meteorite reveals a fine granular structure with the grains irregular in shape and varying somewhat in color from steel gray to dark gray, figure 2. Many of the grains appear to be schreibersite. The outer portion of the material is finer grained than the inner.

[4] Merrill, G. P., Composition and Structure of Meteorites: *Smithsonian Institute, United States National Museum*, Bull. **149**, p. 9.

On cutting the meteorite with a milling machine, a decided difference in hardness was encountered in the different parts of the section. The outer edge was difficult to cut while the inner material was softer. Even the latter portion, however, was not uniform, there being areas of harder material unevenly distributed throughout the entire section. This variation in hardness may be due to an unequal distribution of the different iron-nickel alloys in the various parts of the specimen, though no confirmation of this could be obtained by a microscopic examination of the polished and etched surface.

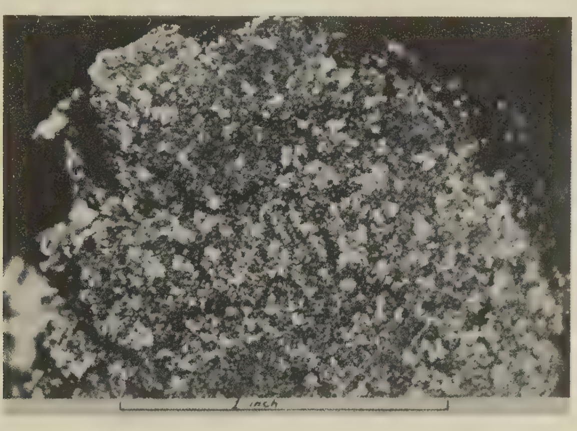

FIG. 2. A polished and etched specimen.

The polished specimen was etched with 7% nitric acid and an examination was made of the etched surface at intervals of one minute during the acid treatment. This process was continued for fifteen minutes and at the end of that time the surface was deeply attacked. At no time during the examination was there any indications of octahedral or Neumann lines, nor of octahedral or cubic cleavage. This lack of structure places the meteorite in the *ataxite* class. Apparently the Soper meteorite is an ataxite with an unusually high schreibersite content.

A portion of the meteorite was sent to W. F. Foshag, Curator of the Smithsonian Institution for confirmation of the identification. In his reply he mentioned that it was quite similar to the Locust Grove, Georgia meteorite and also to the Willemette, Oregon meteorite, though the latter has a coarser texture.

The Soper, Oklahoma meteorite has been divided into two main portions. One piece (1632 grams), is in the Museum of Geology, University of Oklahoma. The other part (1317 grams), is in the meteorite collection of the Smithsonian Institution, United States National Museum. A small piece is in the Nininger collection, Denver, Colorado.

NOTE ON THE CHEMICAL SIMILARITY OF IDOCRASE AND CERTAIN GARNETS

Duncan McConnell, *The University of Texas, Austin, Texas.*

Several years ago, while investigating certain garnets, it became desirable to obtain a more accurate picture of the chemical relationships among andradite, grossularite and idocrase. Because this information may be of interest to other investigators a diagram showing these relations is reproduced here.

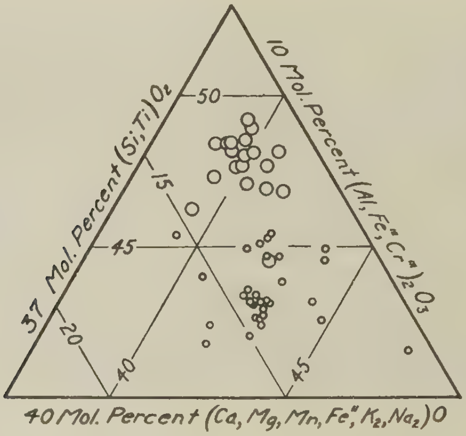

Fig. 1. Diagrammatic representation of non-volatile constituents of idocrase (larger circles) and garnets (smaller circles).

This diagram represents a compilation of most of the seemingly reliable analyses which were recorded from 1909 to 1937. The analyses are plotted in terms of the molecular per cents of the various oxides. The larger circles represent analyses of idocrase and the smaller circles garnets. The 49 analyses are distributed as follows:

Idocrase	19
Grossularite	17
Andradite	10
Schorlomite and melanite	3

One of the analyses of idocrase is somewhat removed from the others and lies in the area occupied by garnets. This specimen is from Almunge, analyzed by R. Mauzelius and described by P. Quensel.[1] The garnet which appears at the lower right of the diagram is a titanium-rich variety from Kuusamo, analyzed and described by O. Zedlitz.[2]

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[1] *Centrb. Mineral.*, p. 203, **1915.**

B. E. Warren and D. I. Modell[3] have demonstrated the structural similarities of garnet and idocrase and this compilation shows the chemical similarities. The most apparent difference in the compositions is the relatively greater abundance of $(Ca,Mg,Mn,Fe,K_2,Na_2)O$ in idocrase.

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[2] *Ibid.*, Abt. A, p. 73, **1935**.

[3] *Zeits. Krist.*, vol. **78,** pp. 422–432, 1931.

Dr. A. E. Alexander, for the past three years ceramic engineer with the Electric Auto-Lite Company of Toledo, Ohio, has resigned to accept an Industrial Fellowship in mineralogy and petrography at the Mellon Institute of Industrial Research, Pittsburgh, Pa.

PROCEEDINGS OF SOCIETIES

MINERALOGICAL SOCIETY OF GREAT BRITAIN AND IRELAND

Thursday, November 3rd, 1938.

Anniversary Meeting. Dr. L. J. Spencer in the Chair.

The following papers were read:—

(1) *On an example of α-quartz showing good cleavages parallel to the three prism faces.* By Dr. J. Drugman.

(2) *On an example of α-quartz crystals with a steep rhombohedron as predominant form.* By Dr. J. Drugman.

(3). *The relation of stellerite and epidesmine to stiblite.* By Dr. A. Pabst (communicated by Mr. F. A. Bannister).

It is shown that stellerite and epidesmine are varieties of stilbite which, though truly monoclinic, are both optically and morphologically pseudo-orthorhombic. A new analysis of stellerite-like stilbite is reported.

(4). *The Adinoles of Dinas Head, Cornwall.* By Mr. S. O. Agrell.

Adinoles associated with spilosites and spotted slates occur at the contact of an albite-dolerite intrusion with black limestone-bearing slates of Upper Devonian age. Four main types are recognized.

1. Normal adinoles—grading into rocks composed essentially of dravite.
2. Adinoles with pseudomorphs, probably after andalusite.
3. Adinoles with globular masses of ankerite showing concentric structures.
4. Polygonal and spherulitic adinoles.

Chemically, the adinoles resemble quartz-keratophyres and their tuffs but the evidence at Dinas Head shows that they are due to the effect of the intrusion on the sedimentary rocks. The first change was purely thermal and was followed by albitization and then by carbonatization, the metasomatizing fluids coming from the dolerite.

(5) *On three australites of unusual form.* By Mr. F. A. Singleton (communicated by the General Secretary).

The paper describes a Tasmanian button form with an exceptionally broad translucent flange; a New South Wales aberrant canoe form in which the normal sculptures of the two surfaces are not differentiated; and a South Australian button core which is hollow and translucent.

(6) *Merosymmetry versus Merohedrism.* By Prof. Austin F. Rogers.

It is often convenient to refer to classes with varying degrees of symmetry within a crystal system and for this purpose the terms holohedral, merohedral, etc., are usually employed. Reasons are given for preferring the suffix-symmetric to the suffix-hedral, thus giving holosymmetric, merosymmetric, etc. These terms were introduced by Story-Maskelyne in 1875, but his nomenclature was unnecessarily complicated.

A simple set of names based upon merosymmetry is presented as a list supplementary to the class names based upon general forms. Since there are only six crystal systems, if we employ that term in the usual sense of a series of closely related classes with geometrical and physical properties in common, there are only six holosymmetric classes.

(7). *Zoned olivines and their petrogenetic significance.* By Dr. S. I. Tomkeieff.

The composition of zoned olivines as determined by measurements of the optic axial angle shows a relation between the olivines and the composition of the parent rocks. Within the olivines the variation is from a Mg-rich centre to an Fe-enriched margin.

(8). *The crystallography of sartorite.* By Mr. F. A. Bannister, Dr. A. Pabst and Mr. George Vaux.

The complex forms of this mineral like those of calaverite have in the past been indexed by various expedients not mutually consistent. Laue and rotation photographs reveal that sartorite is monoclinic, $\beta=90°$ with $a=58.38$, $b=7.79$, $c=83.3$ Å, containing 240 $PbAs_2S_4$ and that it possesses a well-marked orthorhombic pseudo-cell with $a=19.46$, $b=7.78$, $c=4.17$ Å. The abundant measurements made by previous crystallographers can be interpreted satisfactorily on the basis of our x-ray measurements.

NEWARK MINERALOGICAL SOCIETY

The 179th meeting of the Newark Mineralogical Society was held at their new meeting place, 468 Orange Street, Newark, N.J., on Sunday November 6th. Fifteen members and two guests were present.

The topic for discussion was "Unusual Specimens of the Rarer Minerals." The following crystals were exhibited: tellurium; thorite from Easton, Pa.; arsenopyrite from Stirling Hill, N.J.; carnotite (1¼ in.); kainite (1½ in.); ellsworthite; samarskite and betafite. A crystal of witherite (2½ in), showing pseudohexagonal development, from England, and parsonite and phosphuranylite from Bavaria, were also on exhibition.

At the close of the meeting the following officers were elected: President, Mr. R. P. Milburn; Vice-President, Mr. V. Giordano; Secretary, Mr. H. L. Thowless; Treasurer, Wm. H. Broadwell.

Wm. H. Broadwell, *Treasurer*

BOOK REVIEW

A DESCRIPTIVE PETROGRAPHY OF THE IGNEOUS ROCKS, VOLUME IV—THE FELDSPATHOID ROCKS AND THE PERIDOTITES AND PERKNITES. Albert Johannsen. Pp. 524. The University of Chicago Press, *Chicago*, **1938,** Price $4.50.

This is the fourth and last volume of Johannsen's great work on descriptive petrography.

The first volume discusses the constituents and textures of igneous rocks and gives outlines of the many classifications that have been proposed, especially of the newer quantitative classifications, both those based on mineral and on chemical compositions. The final section outlines the author's own quantitative mineralogical classification. The very valuable appendices include a table on miscellaneous definitions, one on textural terms, and tables for the calculation of norms and modes.

The second volume describes the rocks that contain quartz. The third volume describes the intermediate rocks, those that contain feldspar but neither quartz nor feldspathoids; and the fourth volume describes the rocks with feldspathoids, and those that contain neither feldspar nor feldspathoids—the ultramafic rocks.

Johannsen's classification is quantitative, strictly mineralogical and follows, as far as possible, the older mineralogical classifications. It uses volume percentages and makes divisions at 5, 50, and 95 per cent, except for the anorthite content of the plagioclase, where the divisions are at 10, 50, and 90. The classification is plotted on triangles and a double tetrahedron. The four classes are based on the content of the leucocratic constituents. The four orders for rocks containing appreciable amounts of feloids are based on the composition of the plagioclase. Johannsen includes rocks without plagioclase in the first order and includes the albite in perthite with the potash feldspar. For the rocks of class 4, the ultramafic rocks, he bases his four orders on the content of "ores." He divides orders of the first three classes into 26 families on the basis of the proportions of quartz or feldspathoids, K-feldspar, and plagioclase, and plots the results on a double triangle after calculating the leucocratic constituents to 100 per cent. They might be shown thus:

		Proportion of plagioclase in feldspar			
		0 to 5	5 to 50	50 to 95	95 to 100
Quartz	100 to 95	0			
	95 to 50	1	2	3	4
	50 to 5	5	6	7	8
	5 to 0	9	10	11	12
Foids	0 to 5	13	14	15	16
	5 to 50	17	18	19	20
	50 to 95	21	22	23	24
	95 to 100	25			

In class 4, twelve families are based on the proportions of olivine, biotite+amphibole, and pyroxene.

Johannsen divides rocks into three groups according to occurrences: plutonic, hypabyssal, and volcanic, and places some emphasis on the diaschistic rocks. In America, at least, the present tendency is to divide rocks according to texture and to place less emphasis on the diaschistic rocks, and even to question the validity of the conception of diaschistic rocks.

The text gives an outline of the origin and history of the many rock names that have been proposed and brief descriptions with quantitative modal content of minerals, where possible, and chemical analyses. They are arranged according to Johannsen's classification. This enables one quickly to find for comparison descriptions and names of rocks for which he has mineralogical data.

An interesting and valuable feature of the treatise is the large number of reproductions of photographs of petrographers, living and dead.

The four volumes should be much used by every working petrographer.

Esper S. Larsen

NEW MINERAL NAMES

Abukumalite

Shin Hata: Abukumalite, a new yttrium mineral. *Scienitfic Papers of the Institute of Physical and Chemical Research,* Tokyo. No. 822, vol. **34,** pp. 1018–1023, 1938.

Name: From the Abukuma Range, where the mineral was first discovered.

Chemical Properties: A phosphate-silicate of calcium and yttrium; $CaY(Si,P)_2O_8$. Analysis: MgO 0.22; CaO 13.53; MnO 1.13; Fe_2O_3 2.10; Al_2O_3 1.05; Cerium earths 6.45; Yttrium earths 45.98; ThO_2 0.90; SiO_2 20.84; P_2O_5 5.84; $H_2O(-)$ 0.16; $H_2O(+)$ 0.57; CO_2 0.08; F 0.45; Total 99.30. Soluble in cold dilute acids.

Crystallographical Properties: Probably hexagonal. $c=0.7$ (from *x*-ray data). $a_0=5.7$ Å.

Physical and Optical Properties: Color dark reddish brown. Luster resinous to dull. Streak faint brown. Cleavage *c* and *m*, imperfect.

Fracture uneven to splintery. Brittle. H=6.0. G=4.35. Weak radioactivity. Uniaxial, positive. $\omega=1.750$, $\epsilon=1.752$. Extinction parallel to cleavage.

Occurrence: Found in massive forms in feldspar, intimately associated with yttrialite, thorogummite, tengerite and allanite in pegmatite dikes at Iisaka Village, Fukushima Prefecture, Japan.

Discussion: Abukumalite appears to be related to britholite, being the yttrium member, and britholite the cerium member of this series.

W. F. Foshag

Russellite

May H. Hey and F. A. Bannister: Russellite, a new British mineral, with a note on the occurrence and accompanying minerals, by Arthur Russell. *Min. Mag.*, vol. **25,** no. 161, pp. 41–55, 1938, one figure and one plate.

Name: In honor of Mr. Arthur Russell, in recognition of his contributions to British mineralogy.

Chemical Properties: An oxide of bismuth and tungsten, near $Bi_2O_3 \cdot WO_3$. Analyses: Bi_2O_3 68.26, 62.3; WO_3 25.50, 32.1; As_2O_3 0.26, 0.29; Insol. 1.60, 1.6; Ign. loss 4.86, n.d.; Total 100.48; Oxygen 13.13, 13.9.

Crystallographic Properties: Tetragonal, space group D_{2d}^{12}, or possibly D_{4h}^{19}. $a=5.42$ Å, $c=11.3$ Å. Natural crystals not found.

Physical and Optical Properties: Color pale yellow. Fine grained, compact. H=3½. G.=7.35±0.2.

Occurrence: Found as fragments in the jig concentrates of the Castle-an-Dinas wolfram mine, St. Columb Major, Cornwall, intimately associated with native bismuth, wolframite, limonite, quartz, topaz, lithia mica and tourmaline.

Discussion: A comparison of russellite with artificial isomorphous $Bi_2O_3 \cdot WO_3$ indicates that this mineral is a similar isomorphous mixture of bismuth and tungsten oxides.

W.F.F.

Corrections

In the October 1938 issue, page 612, line 21 for "Calgoorie" read "Londonderry". (Dr. Edward S. Simpson has pointed out that there is no such place as "Calgoorie" in western Australia. Page 615 line 4 from Bottom, for "106°C" read "160°C".